

Haptic Feedback to Gaze Events

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M.Sc. Thesis
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December 2018

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Human-Technology Interaction
Biju Thankachan: Haptic Feedback to Gaze Events
M.Sc. Thesis, 55 pages, 6 index and 4 appendix pages
December 2018

Eyes are the window to the world, and most of the input from the surrounding environment is captured through the eyes. In Human-Computer Interaction too, gaze based interactions are gaining prominence, where the user's gaze acts as an input to the system. Of late portable and inexpensive eye-tracking devices have made inroads in the market, opening up wider possibilities for interacting with a gaze. However, research on feedback to the gaze-based events is limited. This thesis proposes to study vibrotactile feedback to gaze-based interactions.

This thesis presents a study conducted to evaluate different types of vibrotactile feedback and their role in response to a gaze-based event. For this study, an experimental setup was designed wherein when the user fixated the gaze on a functional object, vibrotactile feedback was provided either on the wrist or on the glasses. The study seeks to answer questions such as the helpfulness of vibrotactile feedback in identifying functional objects, user preference for the type of vibrotactile feedback, and user preference of the location of the feedback. The results of this study indicate that vibrotactile feedback was an important factor in identifying the functional object. The preference for the type of vibrotactile feedback was somewhat inconclusive as there were wide variations among the users over the type of vibrotactile feedback. The personal preference largely influenced the choice of location for receiving the feedback.

Keywords and terms: Eye Gaze Interaction, Haptics, Vibrotactile Feedback, Smartglasses, HCI.

Acknowledgments

First and foremost I would like to thank the Lord, Almighty, for His everlasting blessing, providing me courage and strength in all my endeavors.

I am indebted to my supervisor Dr. Jari Kangas, for his guidance and support during the period of writing this thesis, providing me insights and points to ponder over, ever motivating me to take small steps and keep on writing. I appreciate his unbounded patience and support throughout this period.

I take this opportunity to express my gratitude to my friend and colleague Deepak Akkil for constantly motivating me with the occasional reprimand, which has finally led to the completion of this thesis. Numerous discussion sessions, brainstorming over the experiments and results, was thoroughly enjoyable and a learning experience.

I acknowledge the role of Prof. Markku Turunen and Dr. Jaakko Hakulinen, who were instrumental in introducing me to the field of Human-Computer Interaction and Interaction Techniques. Attending their courses led me to build strong foundations in the field.

Special mention is reserved for my wife Asha, and my lovely daughter Esther who has always been my pillars of support. Geographical separation for over 4 years was really agonizing, to say the least. The daily video calls were the only panacea which kept me going.

Lastly, I would like to thank my father, mother, and brother for believing in me and constantly providing me a helpful hand. I express my thanks to all my friends in Tampere and Linz especially Jill, Anumita, and Sumita.

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1. Introduction

The advancement of technology and the availability of new devices have led to new ways of interacting with computers. The interaction techniques which have gained prominence in recent years are mid-air gestures, speech/audio, haptics/touch and gaze. Video-based and auditory interaction techniques have been in use for a long time [Blattner et al., 1989; Gaver, 1986; Hemenway, 1982]. However, these interaction techniques suffer from certain limitations which prompt the researchers in the Interactive Technology community to look for alternate and more natural ways of interaction. Gaze interaction technique has huge potential due to its natural and private nature in the interaction. Gaze has been used in text entry, word processing, dictionary applications and many other applications [Majaranta & R  ih  , 2007; Frey et al., 1990; Hyrskykari et al., 2005]. With the availability of low cost and portable gaze trackers such as Tobii EyeX, Tobii Sentry, SmartEye Aurora, EyeTribe and many other such devices, gaze interaction promises immense potential use, where simply looking at the object in real, augmented or the virtual world would be sufficient to interact with them.

Most of our day-to-day activities rely on visual inspection of the surroundings, be it our workplace or home. Inspecting, searching, locating and observing involves different eye and head movements. Sometimes we fixate our gaze to observe more keenly and at other times we scan the surroundings looking for clues. Eye trackers can make use of these eye movements and present the user with different options, helping and aiding the user to take appropriate actions or perform tasks.

The direction and the eye gaze of a person has a strong correlation with the person's intentions and is a "prima facie index of what they are interested in" [Bolt, 1982]. Previous studies related to gaze have mostly concentrated on the behavioral aspect rather than a system component [Bolt, 1980]. With the availability of gaze trackers, it has become easy to estimate and analyze the gaze direction of the user. Thus, human gaze has the potential of being used as an input to perform tasks and to recognize the intent of the user [Duchowski, 2002].

In one of the earlier studies of gaze-based interaction [Jacob, 1990] experiments were conducted in which the task was to select an object from several objects displayed on the screen. Firstly, for the purpose of interaction, the user's eye gaze was combined with pressing of a key to select the object. Secondly, this study also explored the possibility of

using dwell time as an alternative means of selecting the object displayed on the screen. One of the findings of this study was the usefulness of dwell time approach, as it eliminated the ‘Midas Touch Effect’ (unintentional consequences), and also made deselection of an object easy.

Gaze-based interaction is also handy in situations where the hands are occupied and implicit actions with them are ruled out. In such scenario, object selection and subsequent actions can be performed by the eyes with fixation and explicit eye movement patterns called eye gestures. The threshold for dwell time-based eye gestures is reported to range from 150 milliseconds to 1000 milliseconds [Jacob, 1990; Majaranta and R  ih  , 2002]. The downside of dwell time- based object selection is that, this, in some ways takes away the naturalness of interaction and resulting in slow interaction thus degrading performance [Huckauf and Urbina, 2008]. Several alternatives to dwell time-based object selection methods have been proposed, some involving additional modality, others involving additional hardware [Kaur et al., 2003; Surakka et al., 2004; Zhai, 2003].

However, since gaze-based interactions are abstract in nature, providing feedback of gaze interaction is a major challenge, and some form of assistance is required in order to learn the gestures and use them efficiently [Rantala et al., 2014]. Visual feedback is difficult to perceive due to the movement of the eye, and auditory feedback is not suitable in a noisy environment. Apart from that, both visual and auditory feedback mechanisms are not private and can be observed by others too. In order to provide meaningful and efficient feedback, we paired haptic feedback with gaze input. Previous studies involving gaze interaction as input modality and haptic feedback as output modality indicate encouraging results [Kangas et al., 2014c].

Over the years, haptics has evolved as an output modality and has become very popular with various touch-screen based mobile devices such as smart-phones, tablets, table-tops, laptops and wearable devices. Touch as a feedback has been in use in keyboards where the user is able to feel the keys while pressing a key, and also the bumps on certain keys (e.g. key F and J) informs the user that the fingers are on the correct position. Keypads in a smartphone are also enlarged when a particular key is pressed, indicating visually the keypress. In some of the touch-based keyboards in smartphones and tablets, vibration feedback is provided to the user whenever a key is pressed on the keyboard. Alerts in the form of vibrations have now become the de-facto standard for notifying the users. The vibration alerts are used in smartphones, wearable smartwatches and other handheld devices to notify the arrival of new emails, messages, updates or even informing the user

of ‘reaching destination’ in navigational applications. Newer devices are providing targeted haptic feedback based on user’s preferences and interests. Recently, many of the mobile games have started to provide vibration feedback when the user manipulates some object in the game (e.g. hitting a target, kicking, jumping). However, the role of haptics is not limited to the notification function. Haptics is now being used in a variety of ways to provide a truly immersive experience to the user. Haptic feedback is also being used in human-human communication through gadgets, for example, in Apple smartwatch, when a user taps on the profile of a person in the contact list, the selected person feels the taps [Elgan, 2014]. The most compelling reason for haptics gaining prominence is its non-intrusive and private nature. In the future, haptics will add depth and texture to computers, phones, and wearable devices, as well as car dashboards and home automation appliances [Elgan, 2014].

In this study, we present a scenario where a number of objects are visible to the user on a computer screen. The user has to select a target object through gaze and haptic feedback will be provided for the selection. The aim of the study is to analyze how the users associate the haptic feedback for object selection. However, there are various issues that need to be studied for an efficient pairing of these two modalities:

- Type of vibrotactile feedback pattern (Single Tap, Double Tap, Buzz), differentiating the various feedback signals.
- Associating the feedback with the selection of objects through gaze interaction.
- The pleasantness/repulsiveness of the feedback, how the users react to vibrotactile feedback.
- The location in the human body where haptic (vibrotactile) feedback is to be provided.

In our experimental setup, the user tries to identify the correct object through gaze interaction, and feedback is provided through vibrotactile feedback. This brings us to our first research question (RQ1) – *Is the haptic feedback helpful in identifying the functional object in the user’s visual field?* Previous studies have shown that tactile feedback delayed up to 250 ms is best recognized and is associated with target objects, whereas a delay of 500 ms has a detrimental effect on the recognition of the target [Kangas et al., 2014d]. The intent of the user in interacting with the object is very crucial in the interaction. Although the user’s gaze may be focused on an object, it is not necessarily an indication of the user performing any explicit actions with the object. Hence, while

gazing at the object, the user is provided with tactile feedback, indicating that the object is selectable/ready to perform some task. However, it is up to the user to decide, whether the user wants to take any action with the object.

In this study, haptic feedback is unobtrusively provided to the user through specially designed eye-glasses and wristband. The intensity of haptic feedback can be altered by varying the frequency and amplitude of the vibrations to provide distinct feedback such as single tap (a short vibrotactile feedback), double tap (two single taps separated by a short pause) and buzz (vibration for a longer duration). In this regard, the second research question (RQ2) is – *Do the users have any specific preference for the type of haptic feedback (Single tap, Double tap, and Buzz)?* Recent studies have indicated enhanced user experience and reduced errors with the introduction of tactile feedback [Kangas et al., 2014c].

Different parts of the human body significantly vary in the manner in which they react to the sense of touch. Wearable devices capable of providing tactile feedback are available for wrists, belts, back, and head. Through further research, we need to identify the most suitable location for receiving the tactile feedback.. The final research question in our study (RQ3) is– *Do the users have any preference for the location of feedback (wrist/glasses)?* There are a number of smartwatches/activity trackers available in the market which provide notifications on the wrist. We chose to use the wrist (through wristband) and head (through glasses) to provide haptic feedback as they were easy to assemble and readily available.

To reiterate, this thesis seeks to find the answers the following research questions:

- (RQ1) – *Is the haptic feedback helpful in identifying the functional object in the user's visual field?*
- (RQ2) – *Do the users have any specific preference for the type of haptic feedback (Single tap, Double tap, and Buzz)?*
- (RQ3) is– *Do the users have any preference for the location of feedback (wrist/glasses)?*

This thesis has eight chapters. Chapter 2 introduces the Eye Gaze Interaction, starting with the anatomy of eye, how humans communicate with eyes, techniques of eye detection and eye tracking, issues of calibrations and other aspects related to gaze tracking. Chapter 3 introduces the reader to Haptic Interaction, and provides background information on haptics as a modality and haptics as a feedback mechanism. Chapter 4

explores some of the previous studies where haptics has been used in conjunction with gaze, and touches on issues of effectiveness, delays and ideal location of haptic feedback. Chapter 5 is a discussion on the methodology of the experimental user study, and chapter 6 presents the results of the study. Chapter 7 presents the discussion on the results in relation to the research questions and provides insights into design implications, limitations, and pointers for future study. Chapter 8 provides concluding remarks.

2. Eye Gaze Interactions

This chapter introduces eye gaze interaction. The theoretical background behind the working of the eye and the issues concerning the gaze interaction are discussed here.

Eyes are the primary sensory organs of human body, responsible for the perception of vision. It is through the eyes that we see the world. Apart from the basic function of vision, human eyes also play a vital role in communicating with the rest of the world. The eye is, in fact, an excellent pointer [Starker and Bolt, 1990]. A person's eye movements and eye fixations can reveal a lot of information about a person's interest in and attention to things in their surrounding [Just and Carpenter, 1976; Kahneman, 1973]. People tend to look at what attracts them, especially at what they find curious, novel or unanticipated [Berlyne, 1954]. In human-human interaction, eyes are the window to the world. Eyes and their movements are central to a person's non-verbal communication. They express person's desires, needs, cognitive processes, emotional styles, and interpersonal relations [Underwood, 2009].

2.1 The Human Eye

It is with a pair of eyes that humans perceive the sense of vision. Eyes can be considered analogous to a camera as far as capturing images are considered. However, it is the perception faculty that makes the eyes unique. Apart from vision, eyes also play a decisive role in non-verbal communication. Figure 1 shows the outer view of the eye.

- Cornea – The curved transparent outer covering of the eye, enclosing the pupil and iris and is responsible for refracting the light entering into the eye (not visible in Figure 1) [Gregory, 1978].
- Sclera – The white colored region which separates from the iris [Gregory, 1978].
- Limbus – The border of cornea and sclera [Gregory, 1978].
- Iris – The color of the eye is defined by the color of the iris. It regulates the amount of light passing through the retina [Gregory, 1978].
- Pupil – The hole located at the center of the iris. The tissues absorb the light thus giving it a dark appearance [Gregory, 1978].

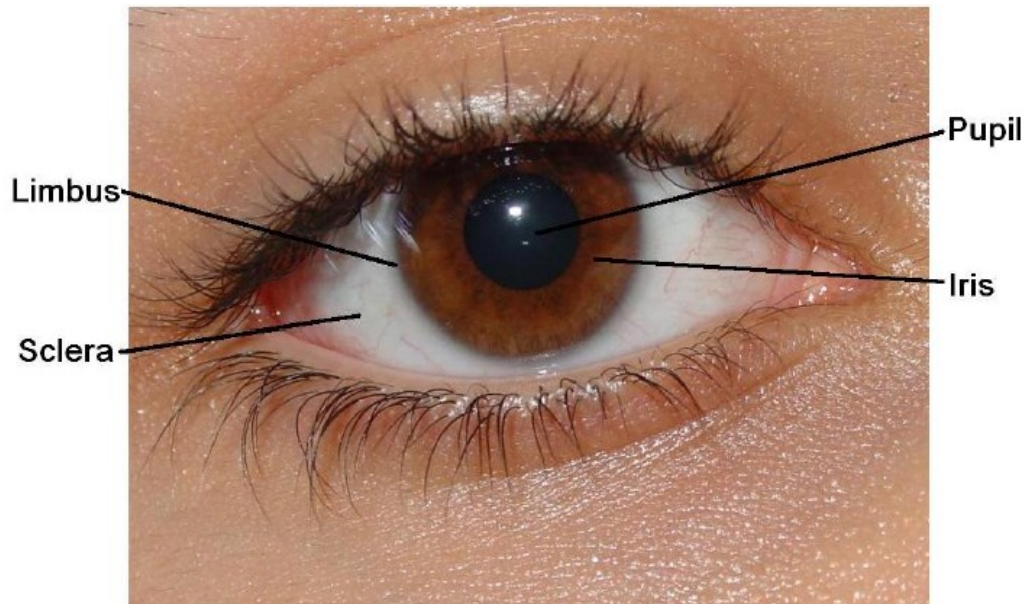


Figure 1: Outer view of the Eye (Cornea not visible from front view)

(image courtesy - pixabay.com)

The movement of the eyes in a particular direction indicates the direction in which the person is looking at. Eyes constantly receive sensory input which is passed on to the brain in the form of electrical impulses. Along with sensory input from eyes, the brain utilizes information from other senses to make a meaningful image of the object. When we look at an object, information from different sources come into play such as our perception, thoughts, and imaginations.[Gregory, 1978]. Previously gained knowledge about the object and inputs from other sensory organs also play a vital role in forming the perception.

In many ways, the human eyes are unique as compared to other primate species. It is only in humans that the sclera (the white region of the eye), which surrounds the iris is in such a sharp contrast [Morris, 1985]. The distinguishing feature between primates and human eyes is that human sclera is devoid of any pigmentation. While the primates have adapted to the coloration of the sclera to camouflage the gaze direction, the humans have white sclera, which helps in enhancing the gaze signals [Kobayashi and Kohshima, 2010]. This vital difference has evolved over a period to enable humans to communicate with a gaze.

The human eye is well understood. A plethora of academic literature is available which gives a very comprehensive description of the anatomy and physiology of the human eye; its optical properties [Snell and Lemp, 1997; Gross et al., 2008]. This section is meant to

provide a basic understanding of the anatomy of the eye to clarify the technology behind gaze tracking.

2.2 The Anatomy of Human Eye

The eye is roughly spherical. Cornea, the outermost part provides protection to the eye from dust particles. The aqueous humor of cornea is responsible for refracting the incoming light and focusing it before passing to the pupil. The iris acts like a diaphragm, which regulates the amount of light passing through the eye by expanding and contracting the diameter of the pupil. The curvature shaped lens, which changes its refractive index by changing its shape to accommodate objects near and far. The light enters through the lens, gets refracted and falls on the retina, which serves as a light-detecting surface. The sensor elements of cornea consist of cones and rods. Cones are responsible for detecting light of high resolution and color, whereas rods detect light with bright field sizes and brightness. The central part of the retina, where the vision is the sharpest is called fovea.

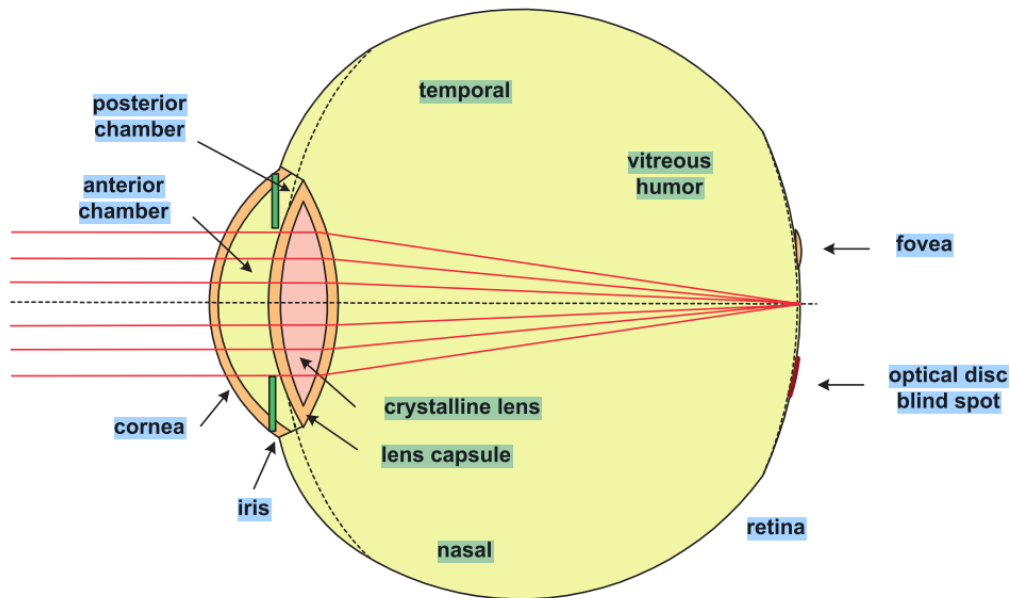


Figure 2: Geometry of Eye [Gross et al., 2008]

2.3 Communicating with Eyes

Apart from the primary function of seeing, humans use eyes as a means of communication. The evolutionary adaptation of Iris also confirms the utilitarian value of eyes in human-human communication. The "language of the eyes" through which

humans communicate, has a vocabulary which is very rich and diverse, can express complex mental conditions encompassing emotions, beliefs, and desires. When someone is looking at something, many higher level factors influence the way where we are looking, for example, often we look at objects of interest instead of fixing our eyes on empty space [Frischen et al., 2007]. Eyes constantly receive sensory input, but we focus our attention only on the object or regions of interest.

Focusing helps us to get finer details and ignore the unnecessary ones. Humans use overt and covert orienting (i.e., redirecting the attention without moving the eye impulsively) to channelize one's focus of attention. Overt orienting is one where the user directs the attention towards the stimuli and is associated with the point of fixation. Overt attention can be detected and measured by an eye tracker [Duchowski, 2007]. Posner in his paper suggests that overt orienting means channelizing the sensory receptors or orienting the body towards a particular direction or object to process the stimuli in an effective manner; whereas covert orienting is the result of the central nervous system [Posner, 1980]. In covert orienting, it could be possible that the user has fixated the gaze at a point, but the attention of the user is not at the point of gaze. Further, Bayliss et al (2004) suggests that adults orient themselves to the direction of eye gaze and without involving any head movement.

2.4 Classification of Eye Movements

A very distinguishing feature of the eyes is their movements, which are both voluntary and involuntary. The human eye is capable of six degrees of freedom which is achieved by six extraocular muscles. These movements help in acquiring, fixating and tracking the visual stimuli. These movements form, also, the basis of non-verbal communication. Eye movements can be classified into four basic types – namely saccadic, smooth pursuit, vergence, nystagmus [Robinson, 1968]. In this section, we will briefly discuss some of the important eye movements which are related to our studies.

- **Saccades** – Saccades are the rapid eye movements ranging from 10ms to 100ms in duration, both voluntary in nature and reflexive in action [Duchowski, 2007]. Even when the eye seems to be fixated on a point, in reality, there are fast random jittery movements. People momentarily fixate their eyes on something, e.g., on a particular key on a keyboard while looking for something without realizing that their eyes have paused before moving forward [Edwards, 1998].

- Vergence - It is the slowest of the eye movements, where the observer's eyes move from the near to the far end in the opposite direction and back again [Robinson, 1968].
- Nystagmus (Miniature movements of fixations) – Are involuntary side-to-side rapid movements (sometimes vertical) where the eyes are not fixated on an object [Robinson, 1968].
- Smooth pursuit – When a person is following a target which is moving, a movement known as pursuit is involved [Duchowski, 2007]. It is with pursuit movements that eyes follow a moving object. The pursuit keeps on updating based on the visual feedback it receives.
- Fixations – Fixations are the most studied and the most used gaze feature. Most of the preliminary studies on eye movements concentrated on using the fixation data. Fixations stabilize the image on the retina and produces a clear vision of the object concerned [Duchowski, 2007]. “The eye fixates the referent of the symbol, currently being processed if the referent is in view” [Just and Carpenter, 1976]. In simple terms, fixations last for at least 100 milliseconds, typically value of these pauses are between 200 to 600 milliseconds. During the fixation, the visual scene is very narrow and of high acuity [Majaranta and Bulling, 2014].

Eye movements have now been studied and analyzed for the past 100 years, and excellent literature is available on the functioning and other intricacies of eye movements [Yarbus, 1967; Robinson, 1968; Hyönä et al., 2003; Findlay et al., 1995]. Our study mainly focusses on the fixation aspect of the eye movement and makes use of this information to identify where the user's gaze is fixated.

2.4 Taxonomy of Eye Detection

This section briefly discusses the taxonomy of eye detection. Once the eyes are detected, they can be further used to gather data about their movements and fixations. However, detecting the eye is a complex phenomenon as it is dependent on the intensity of distribution of the pupils, color of the iris, the shape of the cornea. Moreover, ethnicity and background, angle of viewing, position of the head, color of the eye, texture of the iris, external lighting sources, orientation of the eye socket and the state of the eye (i.e., open/close) are some of the factors that affect the manifestation of the eye [Hansen and Ji, 2010]. Figure 3 shows a broad classification of eye detection [Hansen & Ji, 2010].

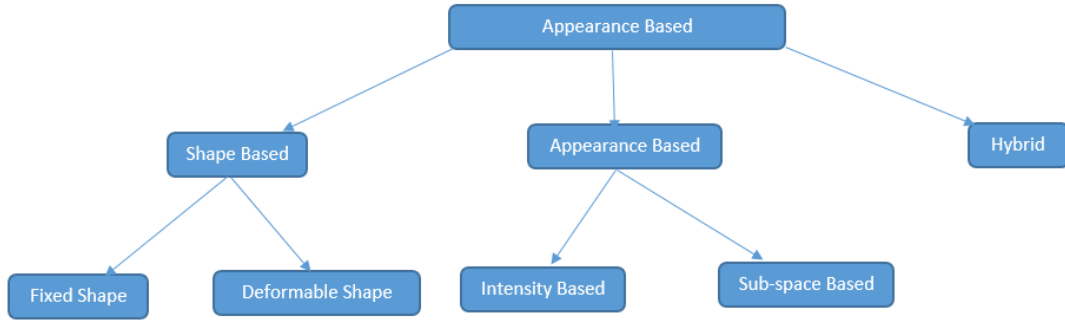


Figure 3: Taxonomy of Eye Detection

2.4.1 Techniques of Eye Tracking

Eye tracking is the general term referring to the measurement of eye orientation. Eye-tracking techniques are carried out based on [Duchowski, 2007] :

1. The orientation of eye relative to head and
2. The orientation of eye in space or Point-of-Regard (POR)

Point-of-Regard (also sometimes referred to as Point-of-Gaze) is the point whose image is formed on the fovea, which is a highly sensitive part of the retina [Borah, 2006]. Figure 4 shows the various parts of the eye. Here the Line of Sight (LOS) (also called visual axis) is the imaginary line which connects fovea to the center of the pupil. Similarly, the imaginary line that connects the center of the pupil, cornea and the center of the eyeball is termed as the Line of Gaze (LOG) (also called optical axis) [Drewes, 2010]. As shown in Figure 4, LOG and LOS cross each other at the center of the cornea. The angle of intersection (4 to 8 degrees) depends on the location of the fovea (above the optical axis), and it varies from person to person. The true direction of gaze understood to be represented by the LOS [Hansen and Ji, 2010].

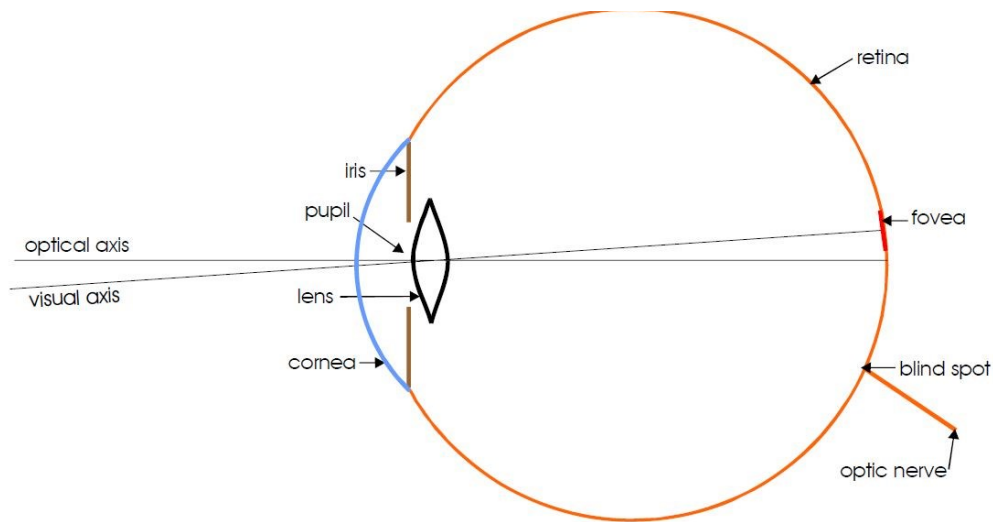


Figure 4: Schematic of the Eye [Drewes, 2010]

Duchowski (2007) categorizes eye movement methodologies involving the use or measurement of namely:

- i. Electro-OculoGraphy (EOG)
 - ii. Scleral contact lens/search coil
 - iii. Photo-OculoGraphy (POG) or Video-OculoGraphy (VOG)
- Electro-OculoGraphy (EOG) method, one of the most popular, consists of attaching electrodes around the eye and measuring the potential difference between them. The recorded potentials at different locations around the eye are in the range of 15 – 200 μ V. These potentials (also known as corneo-retinal/corneo-fundal potential) vary according to the movement of the eye, thus allowing measurement of potential differences [Duchowski, 2007]. With the variation of the magnitude of potential difference, the eye movement can be captured very accurately. However, this type of eye movement measurement is relative to the position of the head, and POR can be estimated only if the relative head position is also measured. This method allows the detection of eye movements even in situations where eyes are not open, e.g., when the person is sleeping. The disadvantage of this system is that the sensors or electrodes being obtrusive are not well suited for gaze interaction [Drewes, 2010]. The downside of this method is that the corneo-retinal potential is remains a variable dependent on surrounding light, color of the eye, tiredness/strain in the eye etc. requiring constant recalibration [Brown et al., 2006].



Figure 5: Example of Electro-OculoGraphy (EOG) Eye movement measurement (Picture courtesy – MetroVision)

- Scleral Contact Lens/Search Coil method is highly accurate and most direct as the sensors are placed directly on the eye. The scleral coils are attached to the contact lens which is worn by the user. Eye movements are captured using either a reflected light from the mirror or by detecting the orientation of the coil in the magnetic field. Although this method is highly precise, however due to the invasive and uncomfortable nature is seldom used in HCI. Their use is restricted only for high precision and high-resolution measurement required in some medical or psychological studies.

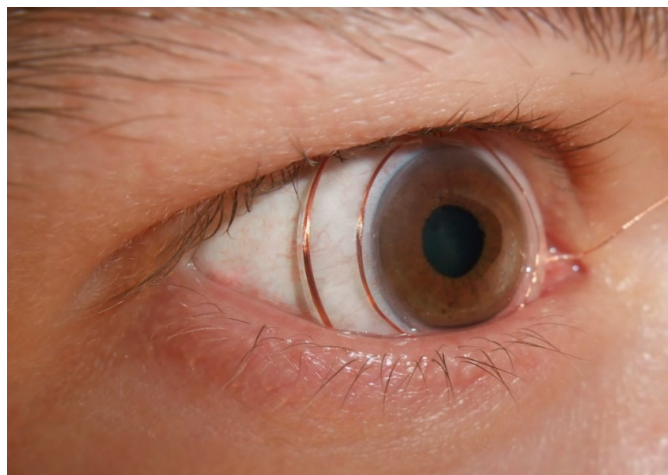


Figure 6: Example of Scleral Contact Lens/Search Coil Eye movement measurement (Picture courtesy – Chronos Vision)

- Photo-OculoGraphy (POG) or Video-OculoGraphy (VOG) method is probably the most popular non-intrusive technique, which utilizes the camera for measuring a number of distinguishing characteristics of the eye such as

rotation/translation, the position of the limbus (the separation between iris and sclera), corneal reflections, etc. [Duchowski, 2007]. Estimating POR is not straightforward as it is not visible and shifts position as the head moves.

There are two techniques for estimating the POR; one, by keeping the position of head-fixed so that head position and POR coincides; two, by collecting various ocular features and eliminating the discrepancies caused by head and eye movements to estimate the POR.

The direction of gaze is estimated by the reflections of the corneal image from the camera. Generally, the camera to capture the images is attached to the head itself. In some of the older systems, the camera is fixed on the table. Due to the shape of the eye, reflection occurs at four different places. These corneal reflections of illumination lights on different eye surfaces are known as Purkinje Reflections (Purkinje Images) [Duchowski, 2007]. The eye tracker detects the first Purkinje image which shows up as a gleam in the camera image, and by comparing the gleam and the pupil. The software for processing the image identifies the position of the gleam and the center of the pupil. The calculation of gaze direction, and its representation on the screen is done with the help of vector which joins the gleam and the center of the pupil [Drewes, 2010]. A glint of the image remains at the constant position for any direction of the gaze for any corneal image. Since the radius of cornea varies from person to person, such a method of estimating the gaze direction requires calibration for each individual.

Moreover, due to the uncertainty of the location of the fovea, calibration is mandated for each individual. For the purpose of estimating the gaze direction, the contrasting feature of the white iris and dark pupil is utilized. Illuminating and detecting the pupil can be done in two ways – the dark and the bright pupil method. In the dark pupil method, the software algorithm identifies the position of the black pupil in the image [Drewes, 2010]. The dark pupil method works best when there is sufficient distinction between the white and black regions of the eye. In cases where this distinction is not well marked (for example in brown or pigmented eyes), bright pupil method is applied where infra-red light is used for illumination, which causes the pupil to show brighter (white) in the captured image, thus making it easier to detect the pupil.

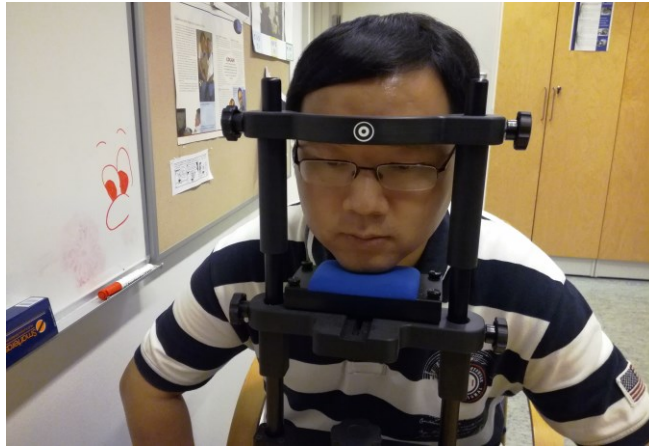


Figure 7: Stationary Eye Tracker

The eye trackers used for medical research are the stationary type, where the user has to rest the chin on a platform to keep the head in a steady position. The other type of gaze trackers is either head mounted or remote. The stationary and remote eye-trackers are very similar in their working except that in the former, the head needs to be stationary. In a head-mounted system, the user wears the tracker on the head, and the camera and infrared lighting are close to the eye. The head-mounted system provides free movement to the user and is suitable for mobile gaze tracking. In a remote system which is attached near the screen, also consists of the camera and infrared light source, is placed away from the user (typically 50 to 80 cm). This system provides free head movement to the user at the cost of degraded gaze quality. Such a system could find application in an immersive environment where the accuracy of gaze direction is not of primary importance, and a rough estimate of gaze direction is sufficient. However, the downside of this system is that the user has to be in front of the screen all the time and thus limiting the mobility.

For our study, we used the TOBII EyeX Eye Tracker, which is attached to the screen. It is a low cost, easy to use eye tracker with an operational range of 45-100 cms. This tracker can be put to use immediately after the brief calibration process and provides hassle-free operation.



Figure 8: Tobii EyeX Eye Tracker (left), Eye-tracker attached to the Monitor (right)

2.4.2 Eye Tracking Calibration

Before an eye tracker can be used, it has to be calibrated for an individual, as there are wide differences in physical eye characteristics such as the radius of the cornea, the location of fovea, etc. During the calibration process, the eye tracker measures physical characteristics of the individual's eye and compares them with an internal model to correctly estimate the gaze data. For calibration, the user is presented with several points (calibration dots) on the screen and asked to fix his gaze on those points. Thereafter, the gaze data collected from the user is analyzed in conjunction with the eye model to fine tune the tracking system. A tracker which is correctly calibrated to an individual is expected to provide accurate and precise results.

Generally, trackers use 9 calibration points, where the user has to gaze for roughly 2 seconds. For more accurate results, more calibration points (12 or 16) are used. Gaze accuracy means the how close are the measured gaze point as compared to the actual point where the user is looking at on the screen (the difference between measured gaze position and real stimuli position). Whereas, precision means the ability of the gaze tracker to reproduce the same gaze point measurement reliably. The accuracy and precision of the gaze tracker are depended on the hardware and the algorithms used to qualify the data [Nyström et al., 2013]. The typical accuracy of the eye trackers is $\pm 0.5^\circ$. The importance of these factors is brought out in Figure 9.

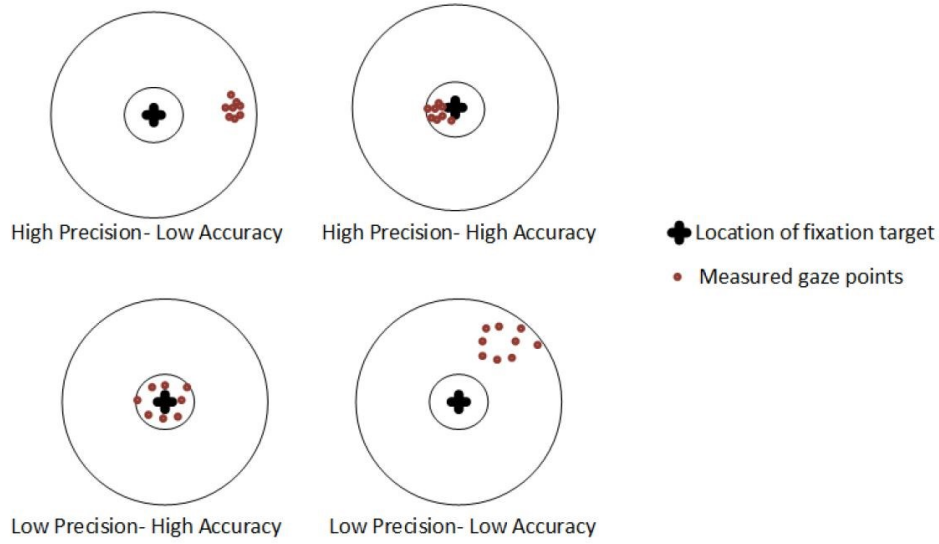


Figure 9: Accuracy and Precision of Gaze Data [Akkil et al., 2014]

Although the use of sophisticated cameras can improve the accuracy of eye trackers, it does not necessarily mean increased accuracy for Human-Computer Interaction [Drewes, 2010]. This gaze accuracy is akin to the accuracy of finger pointing, where the size of the fingertip determines pointing precision.

2.5 Issues in Gaze Tracking

Measuring the movements of the eye and studying its behavior forms the basis of the gaze-based interfaces. The eye movements have been studied for over a hundred years now. However, measuring the direction of gaze and how gaze information can be used in user interfaces is relatively new. Gaze tracking is the term used for measuring the gaze direction. In fact, gaze direction refers to the point of gaze which is being utilized in the field of Human-Computer Interaction. Before we discuss gaze tracking further, let us discuss some of the issues concerning gaze tracking.

2.5.1 Spatial and Temporal Resolution

The measure of how close lines can be resolved in an image is called spatial resolution. The visual acuity measures the spatial resolution of the eye. It represents the clarity of vision and is dependent on optical and neural factors. Temporal resolution refers to the precision of measurement concerning time. Both resolutions are crucial in clearly perceiving an image or a video on the screen. With high spatial and temporal resolutions,

interactive applications requiring user's eye movement are possible [Barattelli et al., 1998].

2.5.2 Fixation, Peripheral Vision, and Attention

Majority of gaze based application utilize fixation as the primary parameter to determine the user's intent. This is because fixations are easy to determine, and can be captured by the eye-trackers distinctly. While communicating with humans, the other person is aware of where we are looking and understands the context based on where the gaze resides without the need to communicate it [Drewes and Schmidt, 2007] explicitly. In contrast to fixation, peripheral vision is a part of the vision which lies outside the boundaries of gaze fixation. Although peripheral vision is not at the center of gaze they play an important role in detecting motion and recognizing forms and structures. Sometimes it could happen that a person is not visually paying attention to an object but his mental attention is directed towards that object. However, most of the gaze-based applications assume that the user's gaze and attention have direct correlation [Duchowski, 2007].

As discussed, gaze based applications mostly rely on fixations, saccades and smooth pursuits for designing gaze based gestures. However, rapid eye movements whether it is intentional or not may pose problems in recognizing the intent of the user. At the same time, long fixation on an object need not necessarily be an indication of the focus of mental attention of the user. An absent-minded user might have gaze fixed on a certain object. However, the user's mental attention is focused elsewhere. Similarly, as in a peripheral vision, the eye gaze is not directly on the object but still manages to gain mental attention.

The control mechanism which controls our shift of attention can be broadly classified into two types: top-down processing (endogenous or goal-driven processing) and bottom-up processing (exogenous or stimulus-driven processing) [Pashler et al., 2001]. In the goal-driven mechanism, the user has a clear idea of what is to be achieved and directs the attention towards the accomplishment of that goal. Whereas, in the case of stimulus-driven mechanism, a stimulus prompts the user to channelize the focus of attention and take appropriate actions. Besides these, Gestalt laws (proximity, closure, similarity, continuation), sequential attention, distinct features (color, shape, size) and motion also play a major role in channelizing the attention of a person.

The shift towards non-command interfaces where the user explicitly issues no command but the computer succinctly tracks the activities of the user and presents scenarios where appropriate actions can be taken by the user. The user-centered interfaces opens up various possibilities for implementing gaze based systems [Hyrskykari, 2006]. These type of interfaces are also known as transparent interfaces, with which the user can interact naturally and efficiently without the need for an intermediate interface element. Such an interface should follow where the user's attention is and should provide cues for interaction.

An interactive system which follows the user's attention is called Attentive User Interfaces, and such interfaces monitor user's behavior through different sensing mechanism [Vertegaal and Vertegaal, 2003]. A simplified model of the steps for attentive user interfaces is shown in Figure 10 [Zhai, 2003].



Figure 10: Steps for Attentive User Interfaces

In some of the gaze-based interactive system, it is assumed that the user will have specific goal during interaction [Bader et al., 2010]. This goal could be selecting an object or pointing to an object, and might also involve additional sub-goals. For such tasks, the user has to fix the gaze on the object for a predetermined period of time (dwell time), which will indicate the user's interest in the object. While the user looks at an object some questions seem pertinent, such as whether the user wants to perform some actions, does the user analyze the object or merely glance at it, if the user's mental attention is focused on the object and such similar questions.

There is also the issue of Midas Touch, which can be very well summarized in Jacobs's (1990) words, *"At first, it is empowering simply to look at what you want and have it happen. Before long, though, it becomes like the Midas Touch. Everywhere you look, another command is activated; you cannot look anywhere without issuing a command"*. Midas touch problem is affected by the "interface style, size and number of elements in the interface, and the image capturing speed, the smaller in size of elements or higher in capturing speed, the more occurrence of Midas touch" [Zhao et al., 2014]. This issue is genuine and poses a challenge in designing gaze based user interfaces. If gaze is to be used as a selecting modality, it should be ensured that once the selection process is

accomplished, the user is free to interact in a normal manner. Dwell time and gaze gestures are some of the solutions to avoid the issue of Midas Touch. Dwell time-based solutions sometimes results in the wrong selection of objects and makes the user uncomfortable and may lead to irritation. As an alternative to avoid Midas touch, a secondary device can be used to confirm the actions of the user, say for example, by using a mouse or a switch, but this in effect mitigates the purpose of eye gaze as a natural modality. Moreover, an additional device involves the use of hands or speech, which is undesirable besides being a burden on the user. Therefore a careful balance is required while applying solutions to Midas touch problem and the user comfort level.

2.6 Gaze Tracking in Human-Computer Interaction

Eye tracking and gaze-based systems have been applied in applications in various fields. The earliest applications involving eye and gaze tracking were related to computer vision, face recognition areas. Later applications include analyzing the gaze data, gaze based interactions where the user could interact with a gaze. Based on the applications of the eye and gaze tracking, these can be categorized into two groups, namely diagnostic and interactive [Duchowski, 2007]. Diagnostic gaze based applications focused on an objective and quantitative method for collecting the point-of-regard of the user. Such kind of gaze data can be obtained while the user is watching television or advertisement, operating display panel in an aircraft, operating with user interfaces, which in turn will help in understanding the analysis of attention of the user [Hansen and Ji, 2010]. In contrast, the interactive applications utilized the user's gaze as an input modality, where the user can perform certain actions on the interface with a gaze. Such systems are also known as gaze-contingent systems, meaning that the system recognizes the activities of user's gaze and may present the user with choices in conjunction with focus of the user [Hansen and Ji, 2010].

Diagnostic applications have been around for quite a long time. Anders (2001) in his study recorded the eye and head movements of the pilot's and analyzed their behavior while scanning for instruments on the control panel of the aircraft. This study captured the eye and head movements of the commercial pilots and studied the various descriptive parameters such as focus on attention areas, fixation duration, transition, scan cycles, etc.

In another study, a Web Browser was developed for persons suffering from extreme physical infirmities wherein the users could act with gaze as an input. This system analyzed the location of the hyperlinks, radio buttons, edit boxes and was operated upon

by the gaze of the user. The results of this study suggest faster browsing experience for the users [Abe et al., 2008].

Gaze-based diagnostic interventions were designed for individuals diagnosed with Amyotrophic Lateral Sclerosis (ALS), where the motor functions are severely impaired. Since ALS affects spinal cord and brain, it affects all the muscle movements, but extraocular muscles which control the eye movements are spared. Researchers have used Eye-gaze Response Interface Computer Aid (ERICA) to help these individuals in their communication functions. These communications included one-to-one interaction, group meetings, making a telephone conversation, accessing the electronic mails, and browsing the web. The ERICA system detected the movements of the eye to control the various functions and activate the commands [Ball et al., 2010].

Bee and Andre (2008) investigated the usability of a writing interface which could be controlled with eyes. They classified the writing pattern into three categories namely typing, gesturing and continuous writing [Bee and Andre, 2008]. The study suggest that continuous writing mostly follows the way human gaze moves. The contrasting difference between typing and gesturing with reference to continuous writing is that in the former the user has to pause with the subsequent entry of the desired text, whereas, in the latter, a smooth, natural movement occurs. As per their study, the results indicate a continuous writing speed of 5 words per minute. Although continuous writing speed was comparatively lower than typing on the keyboard, on the brighter side, it was less exhausting.

There are numerous studies where gaze has been used in diagnostic applications especially for the physically disabled. Some of these studies are: Use of Eye Control to Select Switches [Calhoun et al., 1986], Eye Gaze Interaction for Mobile Phones [Drewes et al., 2007], Command without a Click [Hansen et al., 2003], EyePoint: Practical Pointing and Selection Using Gaze and Keyboard [Kumar et al., 2007].

Interactive systems or Gaze Contingent systems, follow the users gaze and in a way adapt itself to the users gaze. The essence of such a system is to “capture the modes of expression natural to people.” In Bolt’s pioneering work *‘Put-That-There’* the focus was on a system that responds to “what the user is saying (connected speech recognition), where the user is pointing (touch sensitive, gesture sensing) and where the user is looking (gaze awareness)” [Bolt, 1980]. This work opened the Pandora’s Box of immense possibilities for multimodal interaction in an immersive environment.

Adams et al. (2008) investigated novel techniques which allowed the users to navigate and inspect huge images by using eye gaze control. They used Stare-to-Zoom (STZ), where the point of gaze duration determined zooming scale and magnitude on the image. The image was divided into different pan zones, and if the normal saccadic movements occur in a pan zone, nothing happens. A sustained gaze on a specific pan zone results in inward zooming (zooming in). Other methods of control were Head-to-Zoom (HTZ) and Dual-to-Zoom (DTZ), where zooming control of the image was effected and augmented by the movements of the head or mouse [Adams, 2008].

In another interactive application '*EyeGuide: My Own Private Kiosk*,' the researchers designed a system for interacting with large public displays and lightweight head-worn eye tracker. In this system, the user is guided to navigate from one place to another by looking at the subway map on the large display. When the user selects the starting point and destination point, the system provides a route augmented with 'gaze steering', which means that as the user moves ahead and points his current location on the subway map with gaze, additional information such as 'look for the red subway line to the far left' is provided. The additional information is provided through earphones attached to the user [Eaddy et al., 2004].

The *GazeSpace* system by Laqua et al. (2007) was designed for 'able-bodied' audiences, who are similar to expert users and their expectations for the quality of interaction and general usability was comparatively higher. The *GazeSpace* system offers eye gaze as a substitute for a pointing device such as a mouse while navigating through the web pages. The primary information was displayed at the center of the screen, and the navigational elements were at the surroundings. When the user selects an appropriate content, the page would change and the selected content is enlarged and moved on to the main information area replacing the previous content. Even in situations when the system was not able to track the user's gaze, the previous stable state of the interface is displayed, to provide a robust interface. Moreover, continuous visual feedback is provided so that the user is aware which element has the user's focus [Laqua et al., 2007].

Shell et al. (2003) were behind *EyePliances*, an interactive system, where sensors would detect the appliances and connected devices and could interact with them through eyes. This system is based on the premise that people would orient themselves towards the device of interest to communicate with them prior to giving oral commands. Thus, the interaction can be initiated with attention seeking devices when eye contact is established.

Special sensors for detecting the pupil were utilized to determine the user's visual attention. By focusing the gaze directed toward the device of interest, the user indicates to the device to initiate a communication. This is similar to the discussion in a group of people where visual cues provide a signal to other speakers to speak. They also suggest that lack of visual attention towards a device can also be used to perform another meaningful event, e.g., pausing a movie when the user's attention is away from the screen [Shell et al., 2003].

3. Haptic Interaction

Traditionally computer interfaces have restricted themselves with visual and to some extent audio modality. Although these modalities have stood the test of time, yet because of the inherent limitations of visual and audio modalities like unidirectional interaction has left a gap in the field of Human-Computer Interaction. Unfortunately, the sense of touch or haptics was never realized to its fullest potential. It is only in recent times that touch is gaining prominence through touch-enabled handheld mobile devices. However, the origin of haptics research can be traced back to the late 40s [Kwon, 2007] where it was used in Master/Slave teleoperated manipulator systems in hazardous environments. The advancement in computer technology and research in the field of haptics has now enabled realistically visualizing virtual objects. Ongoing research is focusing on developing tactile displays that can allow users to get a feel for the object (texture, roughness, weight, and other properties) as in the real world. However one of the studies pointed out that using haptics feedback alone produces inferior results as compared to other modalities [Morris et al., 2007]. Best results have been achieved when haptics is used in tandem with one or more of different modalities. This chapter discusses some aspects of touch as a modality in Human-Computer Interaction.

3.1 Human Body and Haptics

The word haptics traces its roots from the Greek word *haptikos* (from *haptesthai* which refers to the sense of touch) [Banter, 2010]. The sensory physiology of touch finds its mention in ancient Indian religious texts of Vedas, particularly in Ayurveda, where it is associated with wind, and mentions skin as the primary sense organ. Even the ancient Chinese physicians were familiar with tactile perception [Grunwald, 2015].

Touch is one of the primary senses among the five senses classified by Aristotle. Apart from the sense of touch, a person also gets various feelings from touches such as temperature and pain. So in a way, touch encompasses sub-modalities, which helps to perceive a plethora of senses. In medical parlance, touch is referred in terms of somatic perception to understand the sensory mechanism present. The modality of touch encompasses distinct cutaneous, kinesthetic and haptic systems [Klatzky and Lederman, 2002].

Moreover, touch is also a proximal sense, meaning that the user need not touch to feel the stimuli, for example, sensation occurs with heat radiation or deep bass tones or even vibrations. Although skin is the largest organ in the human body, however, the perception of touch throughout the skin is not the same. The sensitivity to touch differs greatly in different parts of the body. Figure 11 shows the sensory homunculus for touch which is a representation of human body according to touch sensitivity. The body parts which are more sensitive than others can be seen more prominently, for example, hands, lips, tongue and genitals.



Figure 11: Sensory Homunculus for Touch (curtesy National History Museum, Londres)

A force is exerted on the person's skin when humans touch an object (with or without a tool). This force acts as sensory input and is captured through the tissues and nervous system present in skin, joints, tendons, and muscles. The captured information is passed on to the brain leading to the haptic perception. The brain then issues an appropriate command to activate the motor nerves which causes the hands or the body part to react to the sense of touch [Srinivasan, 2005].

When an object is in contact with the hand, the process of relaying this information to the brain can be seen as follows:

1. Tactile information, refers to the sense of type of contact with the object, for example, an affectionate touch in a socially acceptable manner, expressing certain emotions or feelings [Srinivasan, 2005].
2. Kinesthetic information, refers to the sense of position and motion of hands with the relevant forces, for example, feeling the texture of surface while moving the hands over an object [Srinivasan, 2005].

The physiology and psychology of touch is quite a broad topic, and covering them in detail is beyond the scope of this document. A detailed account of the physiology and psychology of touch can be found in [Grunwald, 2015], [Hollis, 2004].

3.2 Tactile Dimensions: Spatial and Temporal Resolution

Spatial and temporal resolution refers to the ability to distinguish the different touch sensory inputs to the body. The human body has limitations in recognizing these sensory inputs and is governed by the threshold limits. The point at which a person can feel the touch stimuli is known as a threshold. This threshold can be classified as - detection threshold or absolute threshold (the smallest detectable level of stimulus) and difference threshold or Just Noticeable Difference (JND) threshold (the smallest detectable difference between stimuli). The way in which spatial limits are resolved is – two-point discrimination method and point-localization method. According to Klatzky and Lederman (2002), “The two-point touch threshold is the minimum distance on the skin where two exact stimuli can be distinctly distinguished”. In this test the participants are required to distinguish if the stimuli are applied to point-1 or point-2, the two adjacent locations on the surface of the body. It has been found that for humans, the distinguishing distance for touch sensitivity is about 1 mm on the fingers [Klatzky and Lederman, 2002]. However, it varies considerably according to the location in the body.

In the point localization method, a touch stimulus is applied at a body location, followed by another stimulus at the same or different location. The participants have to distinguish between the stimuli. The error in the point-localization threshold is found to be 1.5 mm in the fingertip and around 12.5 mm on the back [Klatzky and Lederman, 2002]. Both the methods have been recognized as a good measure of touch sensitivity in humans. Although the point localization thresholds are lower than the corresponding values of two-point thresholds, the measures are highly correlated. Experimental studies have shown that spatial resolution of hand is poorer than the eye and better than the ear. The

figure below shows the two-point and point localizations in a female body. The males also show a similar pattern in the threshold limits [Lederman, 1997].

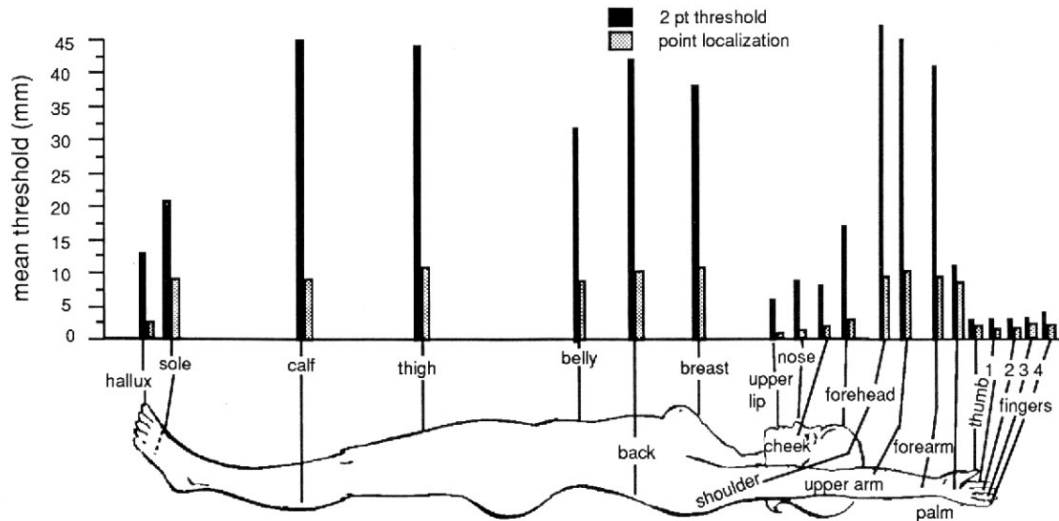


Figure 12: Two-point threshold and point localization threshold [Lederman, 1997]

The Functional magnet resonance imaging (fMRI) of human estimates the temporal resolution to be less than a second [Grunwald, 2015]. The typical value is 5.5 milliseconds, and studies suggest that users can resolve stimuli as small as 1.4 milliseconds. Overall, experimental data suggests hands to be superior to eyes and inferior as compared to ears in the resolution of temporal touch [Klatzky and Lederman, 2002].

The temporal and spatial resolution thresholds were found to be inversely proportional to age, and there was a sharp increase in threshold resolution beyond the age of 65 years. Studies also suggest the effects of age on a spatial and temporal resolution in depreciating manner, and the reasons are ascribed to damaged receptors with age. The most visible change occurs in the Pacinian threshold, as their “response depends on the summation of receptor outputs over space and time” [Gescheider et al., 1994]. This is in tune with many of the sensory functions of the human body, which shows a decline with aging.

3.3 Feedback in HCI

Feedback in general means that the user is informed of the actions performed and the resultant implications of those actions. Feedback is an essential cornerstone in HCI. One of the fundamental examples of feedback is the feeling of touch and the noise created when a key on a keyboard is pressed and released. Here pressing the key is an act, and

the sense of touch and noise is the feedback to the user. Donald Norman (2002) in his classic book, *Design of Everyday Things*, talks extensively on the role of feedback. He introduces the “term *gulf of execution* and *gulf of evaluation* in human-system interaction” [Norman, 2002]. The distinction between the intentions of the user and allowable actions to achieve those intentions is known as the *gulf of execution*. It is a measure of the system’s ability in supporting the user in achieving the desired intentions through real-world actions. This gulf is indicative of the mental model formed in the user’s mental faculties and how user’s actions are translated into the real world to achieve the user’s intentions. The *gulf of evaluation* is indicative of the amount of effort on the part of the user to understand the state in which the system is operating, and the operations needed to achieve the expected results. Bridging the gap between the gulf of execution and gulf of evaluation is key to good design and can make interaction with the system effortless. “A system that makes use of natural mapping between its controls and real-world actions can reduce the gulf of execution and appropriate and timely feedback to user’s action is crucial in bridging the gulf of evaluation” [Norman, 2002].

From the perspective of Human-Computer Interaction, feedback has an interest in “the exchange of information between participating agents through sets of channels, where each has the purpose of using the exchange to change the state itself or one or more others” [Storrs, 1994]. Shneiderman (2005) defines feedback as “communicating with a user resulting directly from the user’s action” [Shneiderman and Plaisant, 2005]. Human-Computer communication should be akin to human-human communication in the sense of a conversational participant, where the user and computer alternately take turns while communicating, having interruptions and cancellation interspersed in the conversation [Pérez-Quñones and Sibert, 1996]. In normal human-human communication, such interruptions and cancellations, could be for example, the person listening could nod his head in confirmation or utter words like *hmm* to indicate that he/she has understood or may even raise eyebrows to indicate confusion or may explicitly say ‘what’ to signal to the speaker that clarification is required.

3.4 The role of Haptics as a Feedback Mechanism

Haptics has been at the center of human interaction due to its unique and special qualities. The sense of touch is bidirectional, salient, expressive, multi-parameter and requires a low cognitive load. With touch user can probe an object to determine its properties, communicate with others, and poke something to elicit a reaction or verify that an action is completed [MacLean, 2000]. The human body is very sensitive to touch, particularly

the fingertips, and through these can detect many activities. The sense of touch is recognized through tactile and kinesthetic information, where the former refers to the nature of contact with the object and latter pertains to the sense of location and movement of arms. In many new applications like flight simulators, virtual reality, medical surgery and rehabilitation haptic modeling and simulation of different physical objects play a pronounced role [Altinsoy and Merchel, 2009]. Touch-enabled devices are making inroads into realizing these applications due to cost effectiveness, availability of software and space. However, many of these applications are still using the traditional modalities which leave much to be desired as far as haptics is concerned.

In the post-WIMP milieu, interaction techniques are moving more towards Reality Based Interactions (RBI), a concept that is unifying and tying together a large number of interaction styles [Jacob et al., 2008]. The real world interactions aim to allow the participants to act on the objects directly instead of issuing a computer-based command. According to Jacob (2008), Body Awareness Skills (BAS) and Environment Awareness Skills (EAS) are the key themes leading to reality-based interactions [Jacob et al., 2008]. Haptics and touch-based systems thus form an important aspect leading to BAS and EAS, wherein the user can physically feel the interaction.

4. Gaze Interaction and Vibrotactile Haptic Feedback

The preceding chapters introduced the gaze and haptics interaction modalities in the field of HCI. As discussed previously, studies combining haptic feedback to gaze events are relatively new and not many studies are available which could throw light on how these two modalities go together. In this chapter we will discuss some of the studies that have utilized haptic feedback to gaze events. While discussing the various studies, we will explore how these studies addressed the questions on the effectiveness of vibrotactile feedback, the temporal limits between gaze events and vibrotactile feedback, effects of feedback location and spatial setup, and finally, how vibrotactile feedback compares with other modalities [Rantala et al., 2017].

4.1 Effectiveness of Vibrotactile Feedback to Gaze Events

In a gaze-based interaction, the human gaze is the input modality. The user can utilize different characteristics of gaze such as fixation, saccade or smooth-pursuit as an intentional control method. The user can fixate the gaze on an object or make a gesture to indicate interest or intention to manipulate the object (perform some related task). In traditional gaze based interactions, the feedback is generally through visual means (e.g., the button changing color or background changing color) to indicate that the system has recognized the user's gaze. A similar mechanism through vibrotactile feedback is possible to inform the user that the user's gaze actions/gestures (events) has been registered. Vibrotactile feedback provides the advantage of being independent of gaze location. Feedback can be termed effective when the user can associate the feedback with the event that caused the feedback. Hence, in the case of vibrotactile feedback to gaze events, the effectiveness will be the degree to which the user can associate the vibrotactile feedback to gaze events (causal relationship).

Kangas et al. (2014a) conducted a study combining gaze gestures with vibrotactile feedback on a mobile phone. Gaze gestures were used as input, wherein the user was given a task to select a name from the contact list and make a call to the selected name. The mobile phone was in an upright position displaying the contact list. Up gesture (i.e., when the gaze stroke moved upwards crossing the edge of the phone and back) resulted in moving up the list by one position. Similarly, Down gesture (gaze stroke crossing the bottom edge of the mobile phone and back) moved the list down to one position. Select (gaze stroke crossing the right edge of the mobile phone and back) gesture activated the presently selected contact from the list. Cancel (gaze stroke crossing the left edge and

back) gesture returned back to the contact list. Different feedback conditions (e.g., feedback to gaze gesture moving out of the device) were tested with the no-feedback condition, and the results of this study demonstrated that vibrotactile feedback was effective and increased the efficiency of interaction [Kangas et al., 2014a].

In another study by Rantala et al. (2015) vibrotactile feedback to gaze gestures was given via wearable eyeglasses. In this study, the participant had to make a gaze gesture moving from the center of the screen to left or right direction. Within this context, the eyeglasses had an advantage that vibrotactile feedback could be provided on the left or right side congruent with the gaze direction. The result of this study indicates that with haptic feedback the users could make gaze gestures faster as compared to the situation with no feedback[Rantala et al., 2015] .

4.2 Time Delay between Gaze Events and Vibrotactile Feedback

Fixing the temporal limits for vibrotactile feedback to gaze events is a complex issue due to the lack of studies addressing area. Failing to identify a suitable temporal limit would result in gaze event being ignored by the user (assuming that vibrotactile feedback as the only feedback mechanism) or vibrotactile feedback not being associated with the gaze event. While fixing a temporal limit, both the system delay and neural processing delay is to be taken into account because the eye movements are fast and frequent. System delay could include, for example, the eye-tracker sampling rate, video processing by the eye-tracker, data transmission rate from the tracker device to the connected computer, generating a vibrotactile pulse, delay in transmission of the pulse and activating the vibrotactile actuator. Neural processing delay (the time taken by the brain in recognizing the signal and sending the signals to the affected area) is dependent on the distance between the location of stimulation and the brain. However, this delay is minimal and is beyond the control of the designer/engineer.

Kangas et al. (2014c) conducted a study to identify suitable temporal limitations for giving vibrotactile feedback to gaze events. In this study, the user had to identify a target object correctly from among different objects (non-target distractors). These objects were displayed boxes on the computer screen. When the user fixated the gaze on the correct box (object), vibrotactile feedback was provided to the user through the actuators. The user had to indicate this target by pressing the spacebar key on the keyboard while looking at the target. The result of this study indicated that there was a significant increase in the

error rates (the user is not able to correctly identify the box) when the delays were around 250-350 ms. With longer delays, the user may have already shifted the gaze from one target to another, thus resulting in incorrectly identifying the box or causing confusion [Kangas et al., 2014c].

In another study by Kangas et al. (2014d), the effect of delay on gaze gestures was studied. The delay of vibrotactile feedback was varied from 100 ms to 400 ms with 50 ms steps. The result of this study showed that acceptable delay is shorter when gaze gestures were used. The task completion times were significantly faster with delays of 150 ms or less. It was found that delays of 200 ms seemed to be the practical upper limit for smooth interaction. As the delays were increased the gaze gestures became difficult to use [Kangas et al., 2014d].

4.3 Ideal location for providing vibrotactile feedback

The location in the body where vibrotactile feedback is presented is a challenging issue. In traditional haptic devices, such as a button or a key on a keyboard, the action performed by the user (pressing the button or key) and the feedback (the sensation of the button press and its recoil) are felt at the same point. In contrast to this, in a gaze-haptic based interaction, the input actions are performed by the eyes and vibrotactile feedback is received at some body-location (for example on the wrist). The choice of feedback location in the body depends on many factors such as - sensitivity of the location to touch, comfort level, the context of the application (for example, cuing for gaze direction), size of the actuator.

Previous studies where gaze and haptic interactions are used have explored different body locations for providing vibrotactile feedback. Vibrotactile feedback was provided on *palm of the hand* [Pakkanen et al., 2008], *fingers* [Kangas et al., 2014; Majaranta et al., 2016], *wrist* [Akkil et al., 2015], *back* [Spakov et al., 2015] and *head* [Kangas et al., 2014b; Rantala et al., 2015].

In the study by Spakov et al. (2015) head and neck to back were used as a location for providing vibrotactile feedback and as a cue for gaze direction. The placement of the actuators is as shown in figure 13, where small circles are the locations of actuators. For providing vibrotactile feedback on the back, the actuators were attached to the chair, and the user could feel the feedback while sitting on the chair. This study used head-mounted

gaze trackers without a visual display unit, and the vibrotactile feedback prompted the users to gaze in a particular direction [Spakov et al., 2015].

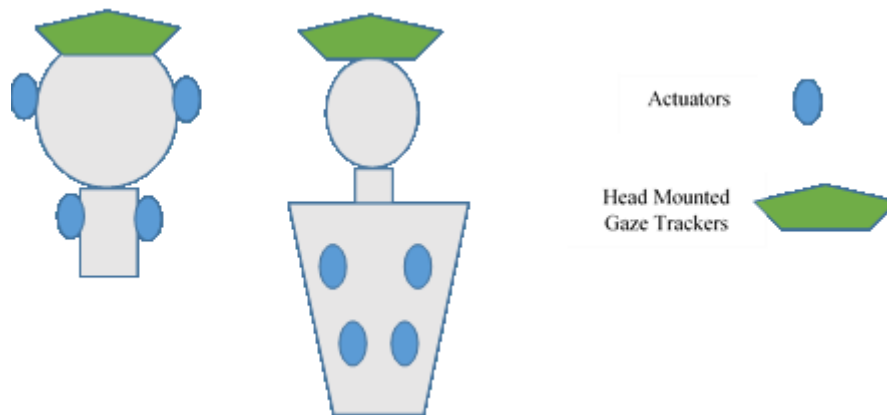


Fig 13- Placement of actuators. The actuators on the head and neck were attached to hair-band. For vibrotactile feedback on the back, the backrest of the chair was fitted with actuators.

The vibrotactile feedback was provided in two modes, *parallel* (when two actuators provided feedback simultaneously) and *sequential* (when actuators provided feedback in sequential order, separated by 50 ms). The result of this study showed no statistically significant difference between the location of the feedback with reference to selection error (missing the target direction) or reaction latency (time interval between the stimulation start and the moment when the gaze falls outside the designated home-box). The results were inconclusive regarding the preference for a particular location of feedback and the users preferred both head-neck and the back [Spakov et al., 2015].

In another study by Kangas et al. (2016), the users interacted with a tablet computer using gaze gestures and in response to these gestures they received vibrotactile feedback on the head (through eyeglasses) and fingers (the user felt the vibrations on the index finger while holding the tablet). The actuators were attached on the left and right side of the tablet and on the two stems of the eyeglasses. The two gestures *right* and *left* designed

for the study involved gaze movement starting from the center of the screen to the right and center of the screen to the left respectively. These gestures were akin to swiping left or right for flipping the pages while reading a book on the tablet-like device. Every time the gaze direction moved from center of the screen to either direction, vibrotactile feedback was provided through the actuators. Additional condition involved incorporating the spatial property meaning that when the gaze direction moved towards the left direction, corresponding actuators on the left side gave vibrotactile feedback (left side of the tablet and left stem of the eyeglass). The result of this study strongly favors vibrotactile feedback in comparison to no feedback condition. Among the vibrotactile feedback also, the spatial condition was preferred over non-spatial condition. However, there was no preference with regards to the location of receiving the vibrotactile feedback[Kangas et al., 2016] .

4.4 Vibrotactile Feedback and other Feedback Mechanisms with reference to Gaze Events

Audio and visual feedback mechanism has been known to improve user satisfaction and help the user in completing the task faster in gaze-based interactions [Majaranta et al., 2006]. However, very few studies have explored and analyzed the role of vibrotactile feedback to gaze events.

Kangas et al. (2014a) have compared conditions where vibrotactile feedback was provided and where no feedback was provided. The results of this study indicate an overwhelming preference for vibrotactile feedback condition. The participants reported difficulty in completing the task and were uncomfortable when there was no feedback. Although some participants disliked the vibrotactile feedback when it was ill-timed with the gaze event, resulting in confusion and not recognizing the feedback to gaze event. The general perception of the participants indicated that vibrotactile feedback helped them in completing the task [Kangas et al., 2014a] .

In another study by Akkil (2015), vibrotactile feedback was compared with visual feedback. There were two tasks: one, simple menu navigation and two, notification. In the menu navigation task, the participants reported no preference for the feedback type. However, in the notification task, a most of the participants favored vibrotactile feedback. While the participants reported visual feedback to be more appropriate as they were

looking on to the watch screen, they were also of the opinion that vibrotactile feedback was clearer and more noticeable [Akkil et al., 2015] .

In an eye-typing study, Majaranta et al. (2016), vibrotactile feedback were compared with auditory and visual feedback. The result of this study indicated no statistically significant difference between the feedback modalities. During the initial experiments, participants were not comfortable having vibrotactile feedback on the wrist and indicated a preference for the finger as the location of feedback. In view of the participant's preference, later experiments showed that vibrotactile feedback performed equally well as compared to auditory feedback [Majaranta et al., 2016] .

In a study on smooth pursuit interaction, where calibration of the eye tracker is not required, vibrotactile feedback was compared with auditory and visual modalities. In the experimental setup, there were two moving buttons, and by following any of these buttons, the user could increase or decrease the color tone; one button decreases the tone of color (black to white), and the other one increased it (white to black). The task was to adjust the level of grey color to match the target color by following a moving button with eyes. The four feedback conditions that were used in this experiment were auditory, vibrotactile, visual and no feedback. The result indicates no statistically significant difference in performance between the feedback modalities. However, vibrotactile and audio feedback emerged as the preferred choice of participants [Kangas et al., 2016b].

In view of the studies discussed in this chapter, we find that in many studies vibrotactile feedback has improved user performance and satisfaction. The vibrotactile feedback is seen to be equally preferred feedback mechanism as the audio or visual feedback. The significance and benefits of vibrotactile feedback stand out when other modalities are unavailable or difficult to perceive [Rantala et al., 2017b].

While there exist studies comparing different feedback modalities and body locations for haptics, there are still several missing links in the puzzle that merits further work. An interesting observation from the different studies is that different researchers have used different types of vibrotactile stimuli (different frequency, duration, intensity, pattern). For example, Rantala et al. used 150 Hz, 20 ms short tap stimuli for the head area, while Spakov et al. used 200 Hz 100 ms stimuli for the wrist. One could imagine that the type of vibrotactile stimulation could influence the suitability and efficiency of the feedback. No previous study has explored the suitability of different vibrotactile feedback patterns for gaze interaction, an open question that this research addresses. This

study explores the use of different types of haptic feedback patterns such as single tap, double tap, and short buzz.

5. Method - Haptic Feedback to Gaze Events

5.1 Interaction Technique

In future with the advancement in technology, it is assumed that objects in real life would be functional through gaze. The haptic feedback provided to the user is to inform the user that some meaningful manipulations can be performed on the object when the user fixates the gaze on the object. This silent communication between the user and the functional object is likely to enhance the user experience in an immersive environment. Thus the current experiment seeks to answer whether the user can associate the vibrotactile feedback with the functional objects. The idea is to answer the questions that if an object is functional, how it should convey the user about being functional. Can the user distinguish between different kinds of vibrotactile feedback? We begin with the assumption that when the user gazes at an object and immediately vibrotactile feedback is provided; then it indicates that the gazed object is capable of manipulation.

In the experimental setup, three different types of vibrotactile feedback are provided to study which one of these is the feedback that is perceived as the most pleasant one. The three vibrotactile feedbacks are Single Tap, Double Tap, and Buzz which was provided on the wrist and glasses. A highly skewed result is likely to indicate a strong preference for a certain kind of feedback among the general users. If the users provide a fractured preference, it should be left to the users the option to select the kind of vibrotactile feedback one prefers.

Through this experiment, we also study if the vibrotactile feedback was timely enough. By saying that the feedback is not timely, we mean that there is a perceivable delay in the user's gaze falling on an object and in perceiving the vibrotactile feedback. Vibrotactile feedback which is not in sync with the gaze on the object is likely to confuse the user, or the user may not associate the vibrotactile feedback with the functional object. It may also happen that the user makes wrong associations about the functional objects and the vibrotactile feedback. A substantial delay in providing feedback is akin to providing no feedback and thus defeat the whole purpose of the experiment.

The third aspect of the study was to understand the preferred location of getting the haptic feedback. In this experiment, we provided the feedback on the wrist and the temporal region of the head through especially designed wristband and wearing glasses (spectacles). The wrist was chosen as one of the locations because there is a number of

wearable devices such as smartwatches and activity trackers, which provide notification (e.g., incoming call, new mail, etc.) to the user. Similarly, the head region was chosen as there are many smartglasses available in the market such as Google Glasses, Snap Spectacles, and Sony smart eyeglass. These smartglasses provide notifications and reports based on different themes directly to the user's eyes. Thus glasses (head region) came as an excellent choice to provide haptic feedback to the users.

5.2 Research Questions

The main purpose of this experiment was to answer the following research questions:

- (RQ1) – *Is the haptic feedback helpful in identifying the functional object in the user's visual field?*
- (RQ2) – *Do the users have any specific preference for the type of haptic feedback (Single tap, Double tap, and Buzz)?*
- (RQ3) is– *Do the users have any preference for the location of feedback (wrist/glasses)?*

5.3 Application Design

For this study, a Windows Form Application in .NET 4.3 framework was developed, which could recognize the gaze of the users and provide vibrotactile feedback on the wrist and specifically designed glasses. The main idea behind the application is to replicate the real-life scenario, wherein a user would interact with different objects and would manipulate them through the gaze. The user would be provided with haptic feedback about his actions through wearable wristband and glasses. The simplistic application simulates the real-life scenarios through images of objects used in real life and provides haptic feedback when the user gazes on specific functional objects. Three objects were selected as a functional object in an image (which may or may not have other objects as well).

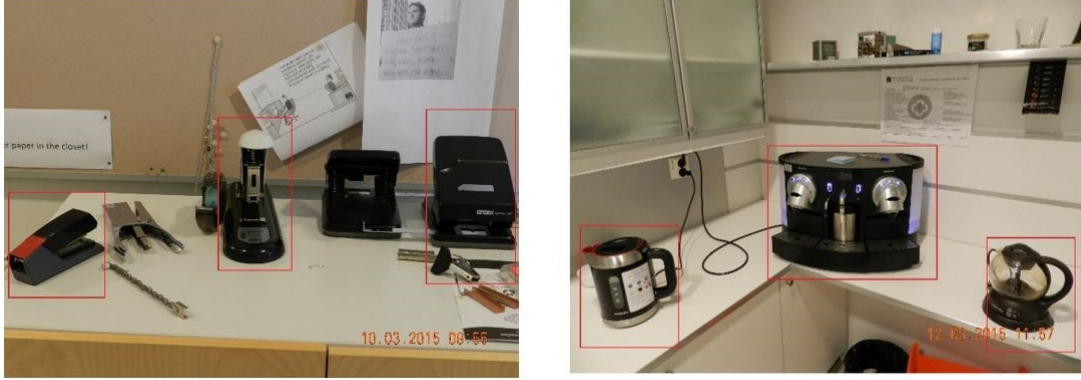


Figure 14: Examples of functional objects used in the experiment

The lower XY-coordinates and upper XY-coordinates were used to demarcate the functional area on the screen, and when the user's gaze falls within this specified area, appropriate feedback is to be provided. In the current experimental setup, we ignore the 'Midas Touch Effect,' and the users are provided vibrotactile feedback every time the gaze falls within the functional area. When the participant's gaze moved away from the functional object, the feedback was no longer present. The desktop application is customizable, and various parameters like the location of feedback, visualization of the gaze panel and other test conditions can be manipulated.

The desktop application was coupled with a prototype wearable glass frame with lenses removed to provide vibrotactile feedback on the head region (borrowed from the setup by Rantala [Rantala et al., 2014]). Two vibrotactile actuators (LVM8, Matsushita Electric Industrial Co. Japan) with a diameter of 0.8 cm were attached to the frame. The actuators were situated towards the edges of the glasses to provide vibrotactile feedback to the temporal region of the head. The position of the actuators eliminates the need to adjust it to the requirements of different users (for example, different head sizes and shapes) and allowing the vibrations to travel through the stems. Thus the users were able to receive the feedback even though the actuators were not in contact with the skin. The actuators used 50 Hz sine wave that provided vibrations without causing any discomfort to the user [Myles and Kalb, 2010]. The duration of the vibrations was set to 20 milliseconds, which were akin to a single tap. A PC running Pure Data (PD) audio synthesis software with a Gigaport HD USB sound card was used to feed the actuators with the audio signals.



Figure 15: Haptic Wrist Band (left) and Haptic Glasses (right)

To provide feedback on the wrist, the actuator was attached to a wristband which could be adjusted as per the requirement of the user. Only one actuator was used on the wrist as opposed to that of the glasses as it was sufficient to perceive the vibrotactile feedback on the wrist.

For the experiment, Tobii EyeX Controller was used, which uses near-infrared light and a camera to track eye movements and gaze points of the user. The desktop application written in Microsoft C# utilizes the EyeX Engine for interpreting the raw gaze data and other user inputs. The user's gaze points which fall within the stipulated rectangular area were deemed to be an indication of the object identification. Thus vibrotactile feedback was provided. All gaze points which fell outside the rectangular area were treated as not identifying the functional object.

5.4 Participants

The participants (Table 1) of the user study consisted of university students in the age group of 20-30 with a mean age of 26 years. A total of 12 volunteers (7 female and 5 male) participated in the user study, of which 9 users had normal vision, and 3 users had corrected vision by their own report. The 3 users who were using spectacles had no problem using the wearable glass prototype over their regular spectacles. Eight participants were familiar with gaze applications, and an equal number of participants had had some experience with haptic feedback (e.g. vibrations on the phone).

Gender	Age	Familiarity with Gaze	Familiarity with Haptics	Normal Vision
Male	30	No	No	Yes
Female	27	Yes	Yes	Yes
Male	25	No	No	Yes
Female	22	No	No	Yes
Male	24	Yes	Yes	Yes
Female	27	No	No	Yes
Male	26	Yes	Yes	Yes
Female	25	Yes	Yes	No
Female	27	Yes	Yes	Yes
Male	26	Yes	Yes	Yes
Female	28	Yes	Yes	No
Female	27	Yes	Yes	No

Table 1: Participant Demographics

5.5 User Study

The study was conducted in a laboratory setting. The distance between the participants and the tracker was approximately 60 cm. All the participants followed the same experimental procedure which is briefly explained below.

1. Filling the basic background questionnaire and informed consent form (Appendix).
2. The participants were introduced to the experiment, the equipment (gaze tracker, wearable glasses, and wristband). The moderator extended support to the participant wearing the devices.
3. Each participant was individually calibrated to the EyeX gaze tracker using the built-in nine-point calibration procedure.
4. The haptic feedback provided on the wrist and glasses were alternately switched to the participants to counterbalance the test conditions.
5. At the end of the experiment, a brief questionnaire relating to the use of vibrotactile feedback in identifying the objects and timeliness of the feedback was asked.
6. The questionnaire was followed by asking users general comments and feedback. The experiment concluded after thanking the user for their participation.

5.6 Experimental Procedure and Tasks

At the onset, the participants were briefed about the experiment, which was followed by filling up the background questionnaire. In the background questionnaire, information such as familiarity with gaze and haptics were collected. The participants were informed about the tasks to be performed, and other instructions were given.

Since the eye tracker has to be calibrated for each participant, the next step in the experiment was the calibration process. The calibration was done by nine-point calibrator program (shipped with the eye-tracker), wherein the participant has to fix their gaze at the designated positions on the screen. Calibration ensures that the participant's gaze is correctly mapped in the screen space.

After the initial calibration of the gaze tracker to the participant's gaze, the application provides to the participant, a set of 10 images selected from real life. The images were so selected as to represent daily usage such as coffee machine, computer screen, light switches and so on. In each image, there were three functional objects. Each of these functional objects was paired with a haptic feedback. The haptic feedback used for distinguishing the functional objects were Single Tap, Double Tap, and Buzz. In each of the images, the participant had to evaluate the different feedback observed and rate the most pleasant feedback. Feedback on the wrist was provided for a set of 5 images and for another set of 5 images feedback was provided on the glasses. Thus there are 10 different images, where the participant had to identify the functional objects and indicate the preferred feedback. The feedback was provided through actuators fitted on the wristband and on the stems of the wearable glasses. Once the participant had indicated the preferred option, the moderator advanced to the next image in the set.

The approximate time taken by the participant to complete the experiment was 20 minutes. As there were no time restrictions, the participants were at liberty to try out the various vibrotactile feedback before confirming their choices and moving ahead with the next image in the set.

After the completion of the tasks, the participants were asked to report on a brief questionnaire relating to vibrotactile feedback, relative to the utility of feedback in identifying the functional objects in the images, timeliness of the feedback. The participants were also asked to provide any general comments and feedback. Figure 15 shows the setup of different components of the experimental setup.

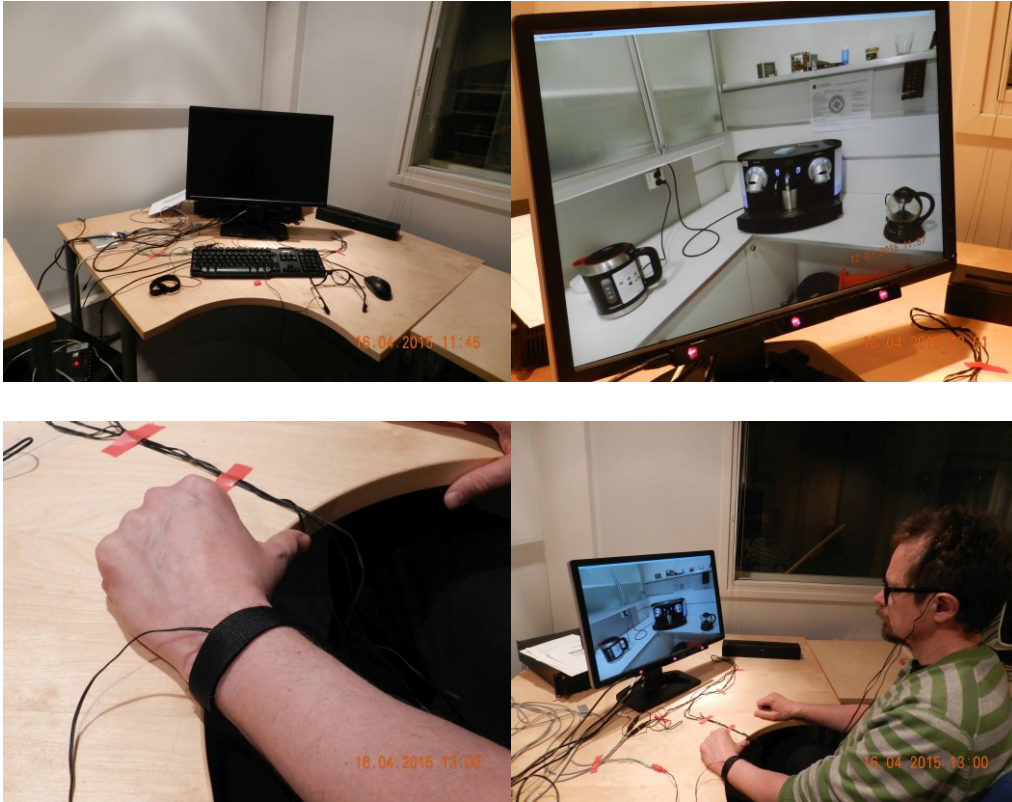


Figure 16: (Top Left) Experimental Setup (Top Right) Display Monitor (Bottom Left) Wrist Band for vibrotactile feedback (Bottom Right) A user participating in the experiment

As the haptic feedback was being provided on the wrist and glasses, counterbalancing was applied to eliminate the order effect. Each of the participants started with a condition which was different from the previous participant. For example, the first participant started with haptic feedback on the wrist, then the next participant started with haptic feedback on the glasses and so on.

6. Results

This section presents the results of the experiment conducted to evaluate the effectiveness of the vibrotactile feedback to gaze events.

Two interlinked factors influence the suitability of haptic feedback to gaze events in identifying the functional objects — first, the perceived usefulness of the feedback to identify the functional objects. Second, the timeliness of the feedback with respect to the gaze events. It should be noted that timeliness of the feedback could, in turn, affect the perceived usefulness of the feedback.

In our study, as many as 4 users *highly agreed* with the statement that haptic feedback was helpful in identifying the functional object. Half the users (6 users) *agreed* with the statement, while 2 users had a neutral opinion regarding the efficacy of haptic feedback. None of the users were in disagreement with the statement that haptic feedback was not helpful. Similarly, 6 users *highly agreed* that haptic feedback was timely, followed by 4 users who *agreed* to the timeliness of the feedback. The other two users were neutral. It should be mentioned here that none of the users were in disagreement on the timeliness of the feedback. Figure 17 shows the response of the participants with reference to (a) the feedback being helpful and (b) the feedback being timely.

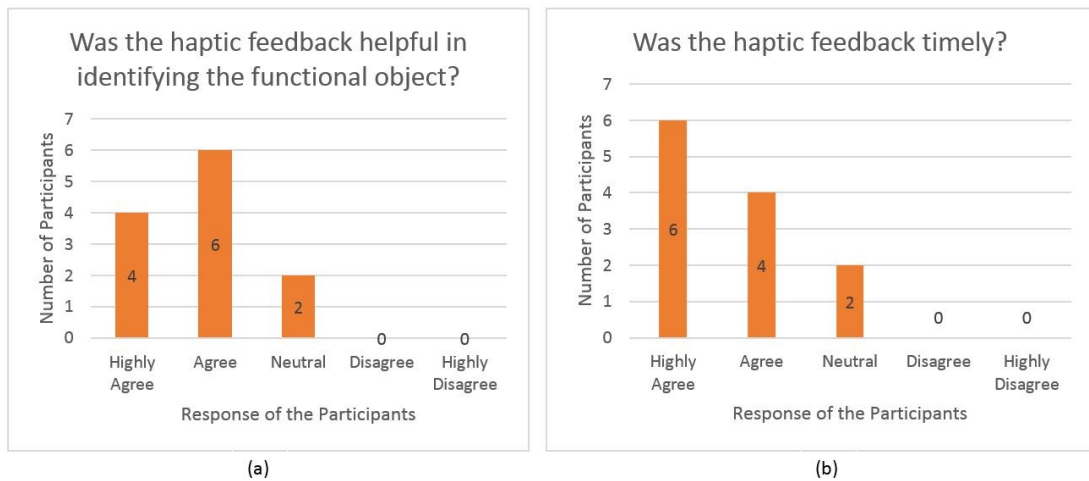


Figure 17: Response of the participants (a) if the feedback was helpful in identifying the functional object, (b) if the feedback was timely.

Vibrotactile feedback was provided to the users on the wrist and, on the wearable glasses. The users were required to indicate the preferred vibrotactile feedback among the options of Single Tap, Double Tap, and Buzz. On the wrist, the most preferred vibrotactile

feedback was Buzz as indicated by 6 users, and Single Tap and Double Tap were each preferred feedback by 3 users as is indicated by Figure 18.

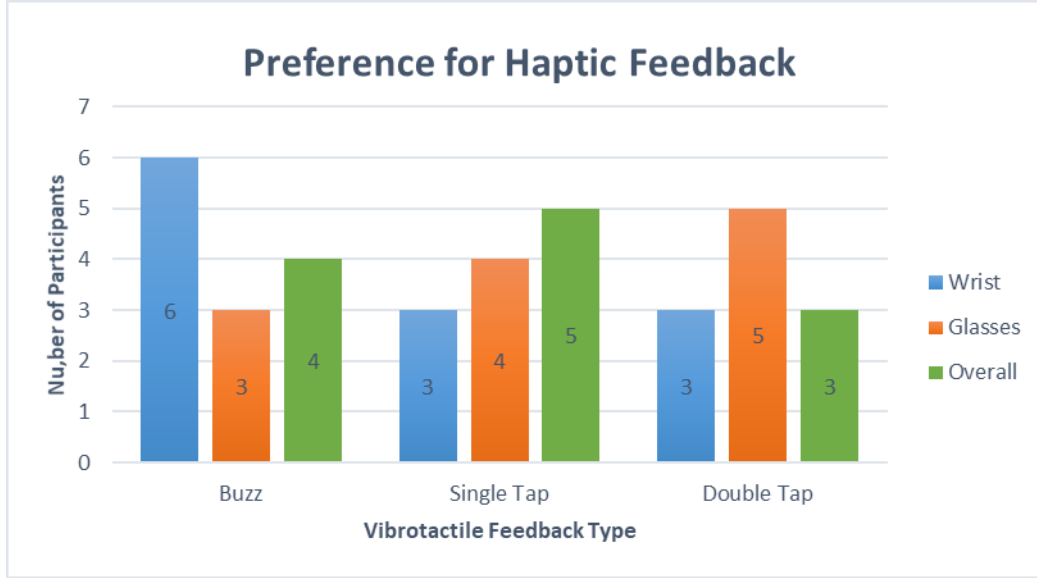


Figure 18: Most Preferred Haptic Feedback on the Wrist, Glasses and Overall preference for the type of feedback.

In contrast, when the feedback was provided on the glasses, the preferred feedback was Single Tap (5 users), followed by Double Tap (4 users) and Buzz (3 users) shown in Figure 18. There are not many variations on the user's preference when the feedback is provided on the glasses.

Among the feedback provided on the wrist and glasses, the overall preferred feedback was Single Tap (5 users), followed by Buzz (4 users) and Double Tap (3 users) as shown in Figure 18.

In our study, we see that, of the 12 participants, 8 participants indicated wrist as the preferred location for providing vibrotactile feedback, whereas 4 preferred glasses as their choice for feedback location.

In the experiment, each participant had to indicate the preference of vibrotactile feedback on the wrist and glasses for the different usage scenarios. In total, there were 5 responses each for feedback on the wrist and the glasses. Hence, overall, for 12 participants there were 60 responses ($12 \times 5 = 60$) on the wrist and 60 on the glasses, which makes the total number of responses to 120. The distribution of the participant's preferences is shown in Figure 19.

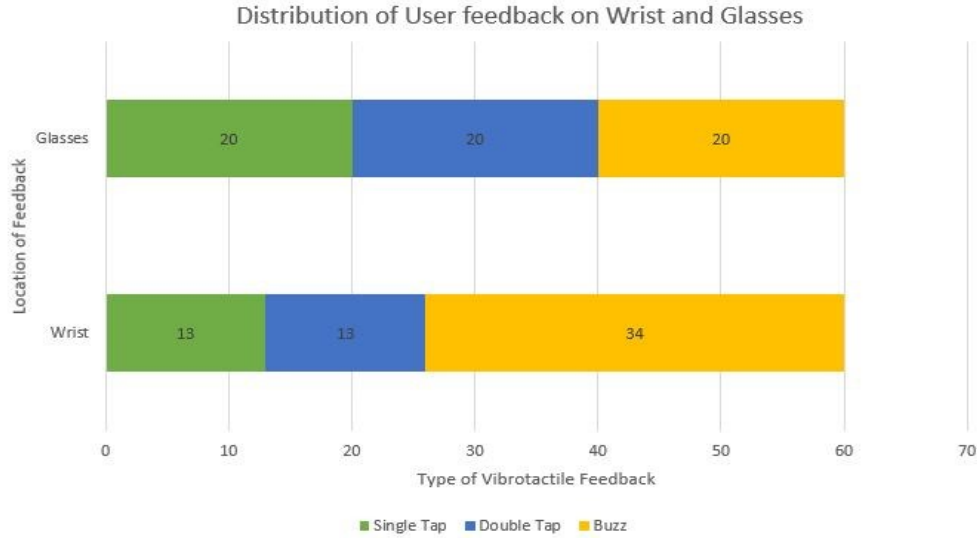


Figure 19: Distribution of user feedback on the wrist and glasses

Table 2 shows the number of responses for Single Tap, Double Tap and Buzz on the wrist and the glasses.

	Single Tap	Double Tap	Buzz	Total
Wrists	13	13	34	60
Glasses	20	20	20	60
Total	33	33	54	120

Table 2 User response for the location of feedback and the type of feedback.

We wanted to see if the location where the feedback was provided and the type of vibrotactile feedback preferences (Single Tap, Double Tap, Buzz) are independent. We conducted a non-parametric Chi-Square test to determine the independence of the variables with the following hypothesis:

H_0 : The location and the type of vibrotactile feedback are independent.

A Chi-Square test was performed and we found the test statistic to be improbably large $\chi^2(2, N = 120) = 6.599$, $p = 0.037$. Hence we need to reject the null hypothesis that the variables are independent.

6.1 User Comments

The user preferences were also consistent with the free-form comments provided by the users.

P1: “It was comfortable on the wrist to identify taps.”

P4: “To wear such glasses is not so comfortable and to have such kind of feeling (feedback) near your ears is also annoying.” From a participant who does not wear corrective eyeglasses.

P5: “(feedback on glasses) felt more natural as it was closer to the eyes.”

P5a: “Haptic feedback given to head may feel uncomfortable after some time of using it.”

P7: “Easy to recognize haptic feedback (on the glasses).”

P7a: “It is good to have haptic feedback in the daily used product as it gives more attention to the object.”

P10: “Buzz and double tap gave a bit of tickling feeling in the head area.”

P11: “Glasses are an integral part of my life. And I would prefer to have feedback embedded in the everyday object I use (glasses).” I perceive feedback more clearly (on glasses) than in wrist.

7. Discussion

Feedback means “sending back to the user information about what action has been done, what result has been accomplished” [Norman, 2002]. Feedback is “traditionally considered to be a communication of system state to the end-user” [Renaud and Cooper, 2000]. Many of the studies have shown that appropriate and meaningful feedback results in improved performance while interacting with computers [Brewster et al., 2007, Majaranta et al., 2006].

We started our study with three key research questions. In this section, we will discuss our findings in relation to the research questions we set out to answer:

7.1 RQ1 – Is haptic feedback helpful in identifying the functional object in the user’s visual field?

In our study, the purpose of haptic feedback was to identify the functional object in the visual field of the user. We presented the haptic feedback to the participants as soon as their gaze fixated on the functional objects on the screen. Based on the subjective evaluation of the participants and observations during the user study, we can conclude that haptic feedback is useful in identifying the functional object in the user’s visual field.

In this experiment, we can conclusively say that haptic feedback was indeed helpful in identifying the functional object. 10 out of 12 participants either agreed or highly agreed that haptic feedback was helpful in identifying the functional object. The remaining two participants were neutral to this statement. Interestingly, none of the participants reported disagreement with the statement.

In general, our results are in line with previous studies supporting the value of feedback in HCI. Specifically, our results support the previous results by Kangas [Kangas et al., 2014c] that instantaneous haptic feedback to gaze fixations is correctly associated with the users. Timeliness of the feedback is a critical aspect in associating the feedback to the causal action. If there is a considerable delay between the gaze event and in providing haptic feedback, then the participant may perceive the haptic feedback to be independent of the gaze event [Kangas et al., 2014c]. In our experiment, the participant agreed with the statement that the haptic feedback provided on the wrist and the glasses were timely. 10 out of 12 participants either highly agreed or agreed with the statement that the haptic

feedback provided was timely. The remaining two participants had a neutral opinion on the timeliness of the haptic feedback.

7.2 RQ2 – Do the users have any specific preference for the type of haptic feedback (Single Tap, Double Tap, and Buzz)?

In our study, no overall preference for any specific haptic feedback type emerged between the participants. However, the most preferred vibrotactile feedback on the wrist was the buzz, and as many as 50 percents of the participants indicated buzz as their choice of haptic feedback. The preference shown by the participants towards single tap and the double tap was same. Nowadays, smartwatches are getting popular, and in these wearable devices, vibrotactile feedback is a popular method of providing notification related information to users. In such a scenario, buzz emerges a preferred choice of many users.

Participants felt the buzz feedback on the wrist were comfortable and easy to recognize and helped the users in identifying the functional objects. The preference for buzz could be because the vibrations were for a longer duration as compared with a single tap or double tap.

The most preferred vibrotactile feedback on the glasses was found to be a single tap (5 participants) followed by double tap (4 participants) and buzz (3 participants). In comparison to the wrist, where the buzz was the most preferred type of feedback, participants preferred a single tap as the preferred feedback type. This could be because head area being more sensitive than the wrist, people prefer to have low-intensity feedback (for example single tap).

Many of the participants receiving taps or buzz on the glasses felt them annoying and were uncomfortable with the idea of getting feedback on the glasses. As mentioned earlier, since the head area is more sensitive, some people disapproved having feedback on the glasses. Nevertheless, smart wearable devices in the form of eyewear are getting popular. Such devices provide a platform wherein both gaze tracking, and haptic feedback capability could be integrated. In such devices, short taps and single taps may be the preferred feedback type than continuous vibrotactile buzz.

Notwithstanding the negative comments, some users who use glasses as a part of their daily wearable objects would prefer to receive feedback on those wearables (Section 6.1

User Comments, P11). This could be because these users are habituated to glasses, and for them, it makes sense to get feedback on these glasses.

7.3 RQ3 – Do the users have any preference for the location of feedback (wrist or glasses)?

In our study, the wrist was the most preferred location for receiving the vibrotactile feedback for the gaze events. 8 (out of 12) participants indicated wrist as the preferred location for vibrotactile feedback whereas 4 participants preferred glasses for receiving the feedback. As people were accustomed to wearing watches, getting feedback on wrist seemed to be natural. The participants reported that it was comfortable to identify the taps on the wrist. Many of the participants felt the vibrations on the glasses were annoying and over a period was irritating. This could be because the vibrations were perceived as stronger on the head area as compared to the wrist.

The study conducted by Kangas et al. (2016a), where vibrotactile feedback was provided on the fingers and head area, reports that both locations are acceptable to the users for receiving the feedback. In our study too, some participants who were using eyeglasses on a regular basis preferred to receive feedback on the glasses. When both the locations are available for providing vibrotactile feedback, the user should be offered the flexibility of choosing the location of receiving the feedback [Kangas et al., 2016a].

Apart from the wrist and head area, other body locations can also be considered for providing haptic feedback. In a previous study, Spakov et al. [Spakov et al., 2015] studied different body locations such as head, neck, and back for providing tactile stimulations. Their study suggests that head, neck, and back were equally efficient in providing feedback on gaze events. In a head-mounted device such as smart glasses or virtual reality headgear, it would be appropriate to provide feedback on the head area whereas on devices such as smart watches or activity trackers, the most appropriate location would be wrist. However, the choice of the preferred location for providing the feedback should be left to the user.

7.4 Design Guidelines

The popularity of wearable devices such as smart glasses and smartwatches are increasing. In the future, it seems likely that wearable devices with built-in gaze tracking and vibrotactile feedback capability will be available in the consumer market. Our study provides some key design guidelines for combining gaze input with haptic feedback in terms of user preferences of the feedback type and feedback location.

1. Gaze input with haptic feedback is a feasible combination of interaction modalities. Haptics is an appropriate feedback modality to gaze events to identify functional objects. Haptics provides a private and unobtrusive feedback modality and should be considered when visual and auditory modalities may not be feasible, appropriate, or preferred.
2. Although a majority of participants indicated wrist as the preferred location for receiving the haptic feedback, there were also few participants who preferred glasses as their choice of receiving feedback (Section 6.1 User Comments, participant P11). Our results suggest that when it is possible to provide the feedback in either of the locations, it would be pertinent to provide the users to choose the location that they prefer.
3. In our study, the majority of the participants preferred buzz feedback when the feedback was provided on the wrist and (single or double) tap feedback when provided through the glasses. Our results suggest that while both wrist and the head area may be appropriate feedback locations, careful design of stimuli is required for the different locations. In the head area, a relatively short vibrotactile feedback may be preferable while in the wrist, the feedback duration could be longer. This can be to an extent explained by touch sensitivity of the wrist and head area. Designers should consider the general touch sensitivity of the body area while designing the appropriate feedback types and one feedback type may not be appropriate for all the different body locations.
4. In our study, there was no overall preference for the type of vibrotactile feedback, and it emerged that users had wide variations in preference for the type of vibrotactile feedback, depending on the location of the feedback. For example, when the feedback was provided on the glasses, roughly equal number of participants preferred single and double taps. The touch sensitivity of the same body location may vary between users [Ackerley et al., 2014] and is dependent on gender, age, and many other factors. This suggests that there

may not be feedback type that would be appropriate for all the users. In the light of this result, it would be ideal to provide options to the user to customize the vibrotactile feedback based on individual preferences.

5. The frequency of the interaction is another important factor to consider when choosing the feedback location and feedback type. In general, haptic feedback should be used when the interaction is infrequent[MacLean, 2008]. Also, the comments from our users reinforce that frequent vibrations may be more acceptable in the wrist than the head area (Section 6.1 User Comments, P5a). Designers should consider the frequency of interactions while choosing the body location and the feedback type.
6. Another important aspect would be to consider user expectations while designing gaze-based interactions. When the user fixes the gaze on a functional object, additional information should be provided to the user based on the user's request. The user may not always be interested in receiving information on every object where the gaze is fixed. Additional information should be provided only when the user indicates the intent of receiving further information.

7.5 Limitations and future work

As is the case with many of the studies, our study had few limitations. First, not all types of feedback were investigated due to the constraints of time and resources. With the availability of a wider variety of haptic actuators, it would be possible to provide a large variety of haptic stimulations such as vibrotactile, pressure, stretch. This thesis focused only on vibrotactile feedback. Future work should investigate the feasibility of other haptic feedback techniques for gaze events.

Second, not all the different possible vibrotactile feedback types and interaction scenarios were investigated. It may be possible that there is a relationship between the functional object and the preferred feedback type. Different everyday objects have varying operation characteristics that users may associate with their desired feedback type (Section 6.1 User Comments, P7a). For example, users may prefer single tap feedback for a functional object like a paper stapler or buzz feedback for a grinder or food processor or small ticking feedback for an alarm clock. Further studies may throw light on the relationship between the characteristics of objects and the feedback type associated with them.

Third, due to the limitations of resources, it was not possible to investigate all feasible locations in the body where haptic feedback could be provided. Wrist and head area were viable locations due to the popularity of wearable devices such as smartwatches and smart glasses. Although, in previous studies, many other locations in the body such as head, neck, and back [Spakov et al., 2015] have been investigated wherein tactile feedback was provided to gaze cues. Other locations such as belt and feet may be considered as possible feedback locations [Pakkanen et al., 2008; Saba et al., 2011]. Additional studies can explore the possibility of using other locations in the body for providing the vibrotactile feedback and the user's preferences for those locations.

Fourth, our study has not taken into account if the user's own experience with using wristwatches or eyeglasses has had any correlation with the preference for the location for receiving the feedback. Users wearing glasses may prefer feedback in the head area (Section 6.1 User Comments, P11). Similarly, users who frequently wear wristwatches may prefer feedback on the wrist. The familiarity with everyday wearable objects and its effect on the user's preference for location need to be investigated further.

Fifth, the small sample size of 12 participants is another limitation of our study. Moreover, the representative sample belongs to the age group of 20-30 years. The sensitivity to touch varies with age, and the threshold for tactile stimulation increases with age [Thornbury & Mistretta, 1981], and our study has not taken into account the aging aspect and sensitivity to touch into consideration. Further research with participants from different age groups could be performed.

Sixth, our study does not make a comparative analysis with other feedback modalities, for example, evaluation of audio or visual feedback responds to gaze events. Previous studies suggest that user's preference may depend on the task and device form factor [Akkil et al., 2016]. Future studies can make a comparison between different types of modalities with gaze events.

Seventh, the gaze-meditated interaction invariably suffers from the Midas touch problem (distinguishing eye movement for interaction from natural eye movement). Also, combined with the vibrotactile feedback on every gaze event after some time would be very annoying to the user (Section 6.1 User Comments, P5a). Our study has ignored the effects of Midas touch. However, it would be interesting to study ways to eliminate this problem in future studies. In one of the previous studies by Lee et al. [Lee et al., 2014] suggests a two-stage selection process using dwell time and half-blink gesture to avoid

accidentally selecting the object. It should be noted that all efforts to eliminate the Midas touch problem involves additional actions on the part of the user, which in turn mitigates the naturalness of the interaction.

Finally, our study was conducted in a controlled laboratory environment. Poor calibration in a real world might affect the identification of a functional object. Moreover, the noises and vibrations in the environment may have a detrimental effect on user's perception of haptic feedback, for example, the user may not be able to notice a gentle tap haptic feedback while on a moving bus. Further experimental studies in the real world would be helpful in identifying the optimal intensity of vibration while providing the feedback.

8. Conclusion

This thesis studied the role of haptic feedback to gaze events wherein the user fixated the gaze on a functional object, and vibrotactile feedback was provided either on the wrist or on the glasses. The vibrotactile feedback was meant to identify the functional object. This chapter provides a broad summary of the research questions and the findings of the experimental study.

The study had the following research questions vis-à-vis the haptic feedback to gaze events:

- *Is haptic feedback helpful in identifying the functional object in the user's visual field?*

Based on the results of our experiment, we can conclude that haptic feedback was helpful for the user to identify the functional object in the user's visual field. A substantial majority of the users reported that haptic feedback helped them in identifying the functional object. This finding is in tune with the results of the previous studies where haptics has been utilized as a feedback mechanism.

- *Do the users have any specific preference for the type of haptic feedback (single tap, double tap, and Buzz)*

In this study, we presented three different types of vibrotactile feedback to the users: single tap, double tap, and buzz. They were presented both on the wrist and glasses. The study indicates that users have no specific preference for the feedback type. Half of the participants reported buzz as the preferred vibrotactile feedback on the wrist, whereas single tap and double tap were equally distributed among the rest of the users. Participants reported that buzz was comfortable and easy to recognize on the wrist.

In the case of glasses, the single tap was the most preferred vibrotactile feedback type, followed by double tap and buzz. The participants were not comfortable with the buzzing feedback on the glasses and felt them annoying. The preference for single tap and double tap on the glasses could be attributed to the fact that head area is more sensitive as compared to the wrist.

- *Do the users have any preference for the location of feedback (wrist or glasses)?*

This experimental study indicates that a majority of users preferred receiving vibrotactile feedback on the wrist. This could be due to the fact that many people have been wearing watches and it seemed to be the natural extension to receive feedback on the wrist. The participants reported that it was easy to recognize the taps on the wrist.

However, there were some participants who were using glasses on a regular basis preferred to receive feedback on the glasses. Most of the participants felt the vibrotactile feedback on the glasses to be uncomfortable.

In conclusion, haptic feedback to gaze based events offers an unobtrusive feedback mechanism to notify the users about functional objects in a real-world scenario. This thesis attempted to answer some of the questions with reference to the type of vibrotactile feedback and locations where feedback should be provided. However, many other questions and concerns which are beyond the scope of this thesis remain unanswered. Future work could explore the usage scenario in a real-world situation. I am hopeful that this work would inspire future researchers in exploring haptics and gaze to work in tandem with other available modalities.

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Appendix A: Background Questionnaire

Gender ☐ Male ☐ Female

Age _____

Age Group ☐ < 20 years ☐ 20 – 30 years ☐ 30 – 40 years ☐ 40 – 50
years

☐ >50years

Are you familiar with gaze technology? ☐ Yes ☐
No

Are you familiar with haptics (touch) feedback? ☐ Yes ☐
No

Do you have normal vision? ☐ Yes ☐ No

If no, what kind of problems?

Appendix B: Evaluation Questionnaire - Haptic Feedback on the Glasses

Sample 1: Which type of haptic feedback was most comfortable to perceive?

☐ Single Tap

☐ Double Tap

☐ Buzz

Sample 2: Which type of haptic feedback was most comfortable to perceive?

☐ Single Tap

☐ Double Tap

☐ Buzz

Sample 3: Which type of haptic feedback was most comfortable to perceive?

☐ Single Tap

☐ Double Tap

☐ Buzz

Sample 4: Which type of haptic feedback was most comfortable to perceive?

☐ Single Tap

☐ Double Tap

☐ Buzz

Sample 5: Which type of haptic feedback was most comfortable to perceive?

☐ Single Tap

☐ Double Tap

☐ Buzz

In the glasses, which one is the most preferred?

☐ Single Tap

☐ Double Tap

☐ Buzz

Appendix C: Evaluation Questionnaire - Haptic Feedback on the Wrist

Sample 1: Which type of haptic feedback was most comfortable to perceive?

☐ Single Tap

☐ Double Tap

☐ Buzz

Sample 2: Which type of haptic feedback was most comfortable to perceive?

☐ Single Tap

☐ Double Tap

☐ Buzz

Sample 3: Which type of haptic feedback was most comfortable to perceive?

☐ Single Tap

☐ Double Tap

☐ Buzz

Sample 4: Which type of haptic feedback was most comfortable to perceive?

☐ Single Tap

☐ Double Tap

☐ Buzz

Sample 5: Which type of haptic feedback was most comfortable to perceive?

☐ Single Tap

☐ Double Tap

☐ Buzz

In the wrist, which one is the most preferred feedback?

☐ Single Tap

☐ Double Tap

☐ Buzz

Appendix D: Post Experiment Questionnaire

	Highly Disagree	Disagree	Neutral	Agree	Highly Agree
Was the haptic feedback helpful in identifying the intractable objects through gaze?					
Was the haptic feedback provided at the same time when you were looking at the object?					

Among all the haptic feedback which one was the most pleasant?

☐ Single Tap

☐ Double Tap

☐ Buzz

Which is the preferred location for providing feedback?

☐ Wrist

☐ Glasses

Why?

Did your eyes feel tired after the experiment?

☐ Yes

☐ No

General Comments
